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NOVEMBER, 1920

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EDITOR: PAUL D. FOOTE
Bureau of Standards
Washington, D. C.

ASSOCIATE EDITORS:

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THE TESTING OF PLANE SURFACES BY INTERFERENCE METHODS.*

BY
C. G. PETERS and H. S. BOYD.

I. INTRODUCTION.

THE planeness of an optical surface is most readily and accurately determined by means of the interference fringes seen in monochromatic light. In making this test it is usually assumed that straight fringes equally spaced indicate that the surface is plane and that curved fringes indicate how much the surface deviates from true plane. These assumptions are correct for normal incidence; but when the surface is viewed obliquely, as is usually the case, they may introduce considerable errors in the determination of planeness. The purpose of the present paper is to point out the best conditions for making the test and the errors introduced by treating oblique incidence as normal.

II. INTERFERENCE OF LIGHT.

If two trains of waves from one point in a source having traversed different paths fall upon a point on the retina of the eye the resultant amplitude of vibration determines the brightness. If they are "in step" maximum brightness results; if, however, the troughs of the one arrive with the crests of the other, destructive interference takes place resulting in relative darkness. If the two trains travel different distances so that the difference in path is some whole number of wave-lengths, then the waves will reach the eye in phase. If the difference in path is equal to some whole

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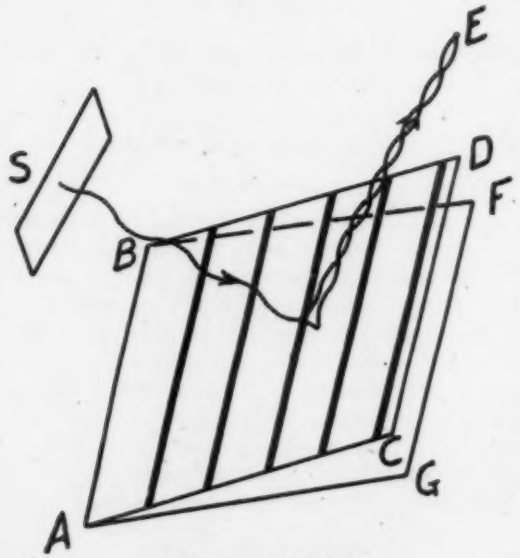
number of wave-lengths plus one-half wave-length, the waves in the two trains will be in opposite phase so that destructive interference takes place. The conditions for interference are realized when light from an extended source S (Fig. 1) falls on a thin transparent film. Part of the light is reflected from the first surface, ABCD, and the remainder is transmitted to the second surface, ABGF, where partial reflection again takes place. Since the wave trains reaching the eye E from these two reflections

FIG. 1.



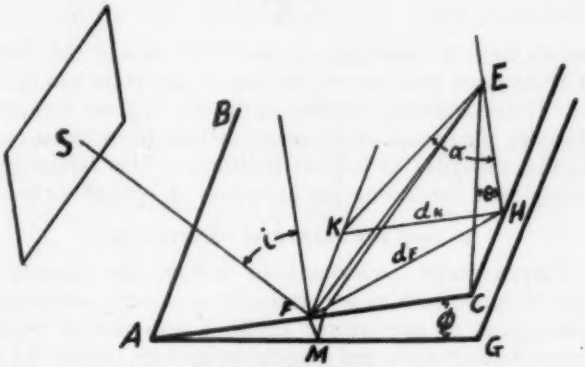
Interference in a thin film.

have travelled over different distances, reinforcement or destructive interference therefore can occur. When white light is used and the film is sufficiently thin, a few brightly colored bands are seen across the surface. If monochromatic light, that is, light of one color or of very limited spectral extent, be employed, alternate light and dark bands or interference fringes extend across the film.

Suppose we have two plane surfaces ABC and ABG (Fig. 2) which are in contact along the line AB and inclined at a slight angle ϕ. A ray of light from a point in the source S reaches the point F, making an angle of incidence i with the normal to the

surface ABC. At F this ray is split into two parts, one of which reaches the eye E along the path FE, while the other, reflected at M, travels along the path FME. The effect produced at the eye by these two parts will depend upon the difference in length $N\lambda$ of the two paths, where λ is the wave-length of the light and N the number of waves, or order of interference as it is usually called. If N is any integer the waves will be out of phase, due to half a wave-length phase change [1] by reflection at the denser

FIG. 2.



Interference in a thin film.

medium, and the point F will in that case appear dark. The difference in path of these two rays coming from F is given by the equation.[2]

$$N\lambda = 2\frac{T + P\tan\phi\tan\alpha}{\sqrt{1 + \tan^2\alpha + \tan^2\theta}} \qquad (1)$$

where P is the perpendicular distance (EH) from the eye to the surface; T is the distance between the surfaces at H; and α and θ are equal to the respective projections of the reflection angle FEH on the two planes through EH perpendicular and parallel to AB.

The numerator of the fraction in equation (1) represents the

[1] Only under special cases is this phase change exactly a half wave length; but it is seldom necessary, as in the present case, to determine its exact value.

[2] Michelson: *Phil. Mag.*, Vol. 13, p. 239; 1882.

thickness t of the film at any point say F and $\tan^2\alpha + \tan^2\theta$ can be replaced by $\frac{d^2}{P^2}$ where d is the distance H to F. Equation (1) then becomes

$$N\lambda = \frac{2t}{\sqrt{1 + \frac{d^2}{P^2}}} \tag{2}$$

from which

$$t = \frac{N\lambda}{2}\sqrt{1 + \frac{d^2}{P^2}} \tag{3}$$

Therefore from a knowledge of the order N and the distances d and P the exact thickness of the film at any point can be determined. If one boundary surface of the film is plane it is possible to determine the nature of the other surface from measurements of the film thickness at various positions. This is the method commonly used for testing the planeness of optical surfaces.

III. TEST FOR PLANENESS OF SURFACES.

1. *Perpendicular Incidence.*—In testing the planeness of polished surfaces, such as are produced on prisms, surface plates, precision gages or micrometer anvils, a test plate is placed in quite close contact with, and slightly inclined to, the surface to be tested, thus forming a thin wedge-shaped film discussed in the previous section. This test plate is of glass, one surface of which has been polished accurately true plane and tested against a master true plane or liquid surface of large extent. The accuracy of the test is of course limited by the irregularities of the test plate surface. It is very difficult to make glass surfaces fifty to seventy-five millimeters in diameter plane within .25 micron, and to reduce this error requires exceptional skill. For ordinary work, however, test plates of the accuracy just mentioned are sufficient, but when it is necessary to determine irregularities of a few hundredths of a micron in the surface under test, great care must be exercised in selecting and testing the test plate.

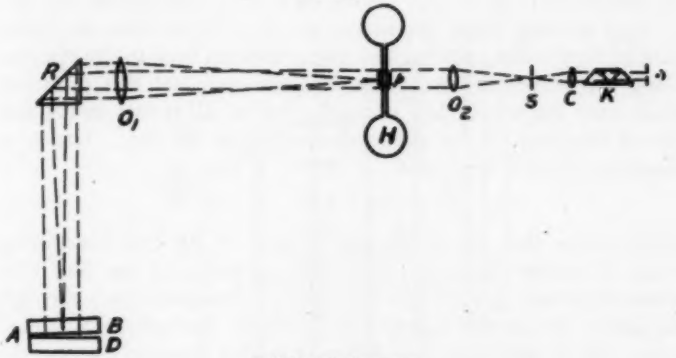
In order to give a definite value to the wave-length λ the thin wedge-shaped film of air, formed between the plane surface of the test plate and the surface under test, is illuminated with monochromatic light. A convenient source of monochromatic light is a bunsen flame in which is inserted a piece of asbestos

soaked in a salt solution, or a ground glass plate illuminated either by a helium lamp operated on a 5000-volt A. C. circuit, or by a mercury vapor lamp covered with a green absorption screen. The wave-lengths of the most effective visible radiation from these sources are approximately:

Sodium (yellow) = .589 micron
Helium (yellow) = .588 micron
Mercury (green) = .546 micron

A colored glass screen illuminated by an incandescent lamp or ordinary daylight may be used as a source if high precision is not

FIG. 3.



Pulfrich interferometer.

desired, but the light will not be sufficiently monochromatic to allow assignment of a definite value to the most effective wave-length.

A very convenient instrument for illuminating the film and at the same time viewing the interference fringes on the film is one designed by Pulfrich[3] and shown in Fig. 3. The light from a helium lamp H is focused upon a small total reflection prism p. After being collimated by the lens O_1 it is reflected by the prism R down to the interferometer ABD which is in the focal plane of the lens O_1. The rays reflected by the film surfaces are brought to a focus by the lenses O_1 and O_2 upon the slit S and images of the interference pattern and the reference marks on the

[3] Pulfrich: *Zeits. f. Inst.*, Vol. 18, p. 261; 1898.

test plate are viewed with the eyepiece C. The direct vision prism K separates the fringe patterns due to the helium light of different wave-lengths. A pair of crosswires located at S and operated by a micrometer head make it possible to measure small displacements of the fringes from the straight reference lines ruled on the test plate AB. With this instrument and an exceedingly true test plate, the planeness of an unknown surface can be measured with an accuracy of .025 micron. The only objection to the instrument is that the field is limited to about 2.5 cm., so in testing a large surface only a small portion can be seen at one time. Instruments of similar optical design described by Schultz,[4] Shönrock,[5] and Laurent [6] eliminate this objection by having fields of view as large as 25 cm. With these four instruments the rays of light coming from the source to the film surfaces are made parallel by the lens systems and when reflected back to the eye pass along the perpendicular to the first surface; and this condition holds over the whole field of view, that is, all points in the film are at the foot of the perpendicular from the eye. Hence in equation (3) d is zero, and

$$2t = N\lambda \qquad (4)$$

which states that the difference in path of the two interfering trains is simply equal to the double thickness of the film (the double distance signifies that light travels down and back through the film). From this equation it is evident that where N is constant, that is along any one fringe, t is also constant; hence, the fringes trace lines of equal separation of the two surfaces.[7] Starting from the line of contact AB of the two plane surfaces (Fig. 4) and moving to a wider part of the film, when $2t = \lambda$ interference takes place and the first dark fringe f_1 will be a straight line parallel to AB. When $2t = {}^3/_2\,\lambda$ the wave trains reinforce each other and a light fringe is produced. Moving to a still thicker part of the wedge where $2t = 2\lambda$, a second dark fringe f_2 will occur, etc. From this, it is evident that if the surfaces are

[4] Schultz: *Zeits. f. Inst.*, Vol. 36, p. 252; 1914.

[5] Brodhun and Schönrock: *Zeits. f. Inst.*, Vol. 22, p. 355; 1902.

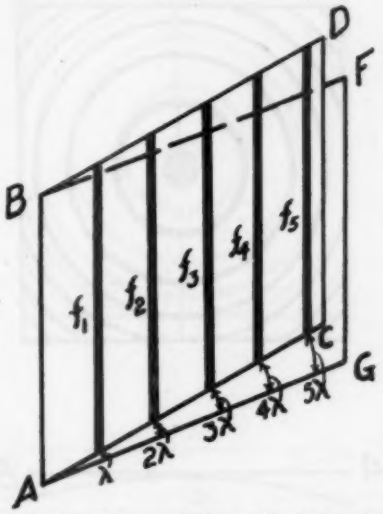
[6] Laurent: *Comptes Rendus*, Vol. 96, p. 1035; 1883.

[7] The fact should be stressed here, however, that the fringe marks the line of constant thickness of the film only when the direction of view is perpendicular to the film over the whole film. Observed obliquely, straight fringes do not indicate that the tested surface is plane, as shown below.

plane the fringes will be straight lines, equally spaced and parallel to the line of intersection of the surfaces. The next dark fringe always occurs on passing to where the double separation increases by λ, hence, the distances between fringes depends on the inclination of the surfaces.

If a plane surface be brought in contact with a convex spherical surface (Fig. 5) then at C the point of contact, $2t$, is equal to zero. Radially from this point the separation of the surfaces increases uniformly in all directions, so the fringes, and hence the lines on which $2t = N\lambda$, are concentric circles around the point

FIG. 4.



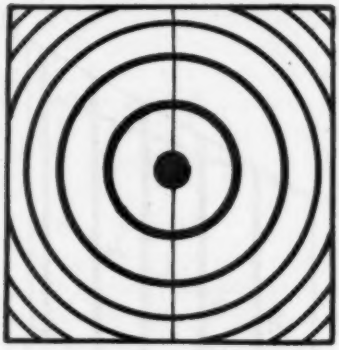
Fringes observed at normal incidence from plane surfaces.

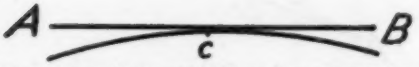
of contact as a centre. On any ring the distance of the spherical surface from the plane is equal to the number of the ring counting from the point of contact times $\frac{\lambda}{2}$. By pressing down at A, the plane surface can be made to roll on the spherical surface shifting the point of contact and with it the centre of the ring system in the direction of A, or, toward the point of application of the pressure. With a convex surface therefore the centre of the ring system lies at the point of minimum separation.

If one of the surfaces be concave and spherical (Fig. 6), a similar system of concentric circular fringes is produced, but in this case the centre of the system lies at the point of maximum separation. Pressing down on A causes the centre of the ring system to shift toward B, the direction of increasing separation, away from the point of application of the pressure. Thus a slight pressure on one edge of the plane surface AB serves to indicate whether the curved surface is convex or concave.

With one surface plane and the other irregular the fringes are irregular curves each of which follows the line of equal separation

FIG. 5.





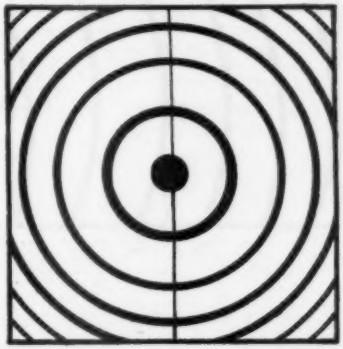
Fringes observed at normal incidence from convex surface.

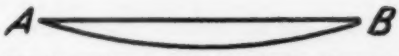
of the surfaces. Whether the irregularity is a projection or depression can be determined by applying a slight pressure to one edge of the upper surface and noting the direction of shift of the fringes.

The amount a curved surface deviates from a true plane can be readily estimated as follows: Draw a straight line FK (Fig. 7) across the centre of the true plane surface, parallel to the line of contact AB of the surfaces. Bring this line tangent to one of the fringes at say the point H. It is evident that this line represents

the direction a fringe through H would take if the irregular surface could be converted into a plane tangent to the irregular surface at H. The fractional part of the distance between two fringes by which the fringe EL deviates from the straight line FK gives the fractional part of a half wave length by which the irregular surface deviates along FK from true plane. With AB as the line of contact, the point F is estimated to be one-fourth wave-length above and K one-half wave-length below the surface tangent at H.

FIG. 6.





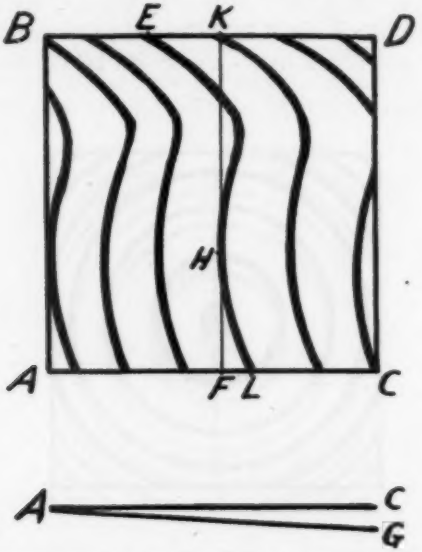
Fringes observed at normal incidence from concave surface.

2. *Errors of Interpretation.*—Although the theory is quite explicit, it is a very common mistake to assume that straight fringes always indicate planeness, when a surface under test is placed on a true plane; and conversely, curved fringes indicate that the surface is not a true plane. Both of these interpretations may be wrong. For example, the operator will view the light reflected by the film under oblique incidence; and to make sure that the fringes are straight, he may lower his eye to sight along them. Or, the fringes from one position appearing curved, he may shift

to another and find them quite straight, then draw his conclusions from what he observes under these, to him, best conditions.

It is important to know something about the magnitude of the errors which may be introduced by the assumption that

FIG. 7.



Fringes observed at normal incidence from irregular surface.

straight fringes always indicate planeness and curved ones indicate curvature of the surface tested. The treatment of this falls under the general case shown in Fig. 2 where the thickness of the film at any point is given by equation (3),

$$t = \frac{N\lambda}{2}\sqrt{1 + \frac{d^2}{p^2}}$$

which goes over, for normal incidence, into equation (4),

$$t = \frac{N\lambda}{2}$$

Suppose, with the eye at E (Fig. 2) a straight fringe is observed along FK. With one of the film surfaces true plane, how much does the other diverge from a plane between F and K? The actual

error in determining the thickness t at any point by (4) when (3) should be used is obviously

$$E = \frac{N\lambda}{2}\left(\sqrt{1 + \frac{d^2}{P^2}} - 1\right) \tag{5}$$

and the relative error,

$$\epsilon = \frac{E}{t} = 1 - \frac{P}{\sqrt{P^2 + d^2}} \tag{6}$$

The actual deviation from planeness between F and K is

$$X = t_F - t_K$$

The error introduced by using (4) instead of (3) is

$$\begin{aligned} S &= \epsilon_F t_F - \epsilon_K t_K \\ &= X\epsilon_F + (\epsilon_F - \epsilon_K)t_K \\ &= X\left(1 - \frac{P}{\sqrt{P^2 + d_F^2}}\right) + \left(\frac{P}{\sqrt{P^2 + d_K^2}} - \frac{P}{\sqrt{P^2 + d_F^2}}\right)t_K \end{aligned} \tag{7}$$

This equation is seen to be consistent in that S becomes zero for normal incidence at both F and K, in which both d_F and d_K are zero.

Sighting along a line from a normal position over K, $d_F = 0$, $\therefore \epsilon_K = 0$.

$$\begin{aligned} S &= \epsilon_F (X + t_K) \\ &= \epsilon_F t_F \end{aligned} \tag{8}$$

which states that the error in determining how much the tested surface deviates from the plane is simply equal to that in determining the thickness of the film at F by using equation (4) instead of (3).

If one observes the fringe obliquely at both F and K (d_F and d_K increasing and at the same time approaching equality), we have, for a given length FK, the error arising from the true deviation X increasing with the angle of incidence, while that arising from the thickness t_K of the film is decreasing. Consider some numerical examples:

(a) With the eye 25 cm. above the centre of a 15-cm. surface being tested on a true plane, and viewing a diametral fringe

$$P = 25,\ d_F = 7.5,\ d_K = 0$$

Applying (7), $$S = .042\ X + .042\ t_K$$

showing that the surface under test judged to be plane is really convex by more than 4 per cent. of the film thickness t_K at the centre of the plate. With such a method, since S decreases with t_K the fringes should change in curvature as the plate settles.

(b) With the eye moved back 25 cm. in a direction at right angles to the fringe—P remaining constant—and viewing the centre K and farthest edge F, $d_F = \sqrt{25^2 + 7.5^2}$ $d_K = 25$, we have from (7)

$$S = .308\ X + .015\ t_K$$

(c) With the eye moved back 50 cm. instead of 25,

$$d_F = \sqrt{50^2 + 7.5^2}\quad d_K = 50.$$

$$S = .577\ X + .004\ t_K$$

A comparison of (a), (b) and (c) shows that the error arising from the actual deviation X increases rapidly with slanting inspection, while the error arising from the thickness t_K of the film decreases rapidly.

If in (b) and (c) one sights respectively along instead of across the fringes

(d) $$d_F = 32.5\quad d_K = 25$$

$$\therefore S = .39\ X + .10\ t_K$$

(e) $$d_F = 57.5\quad d_K = 50$$

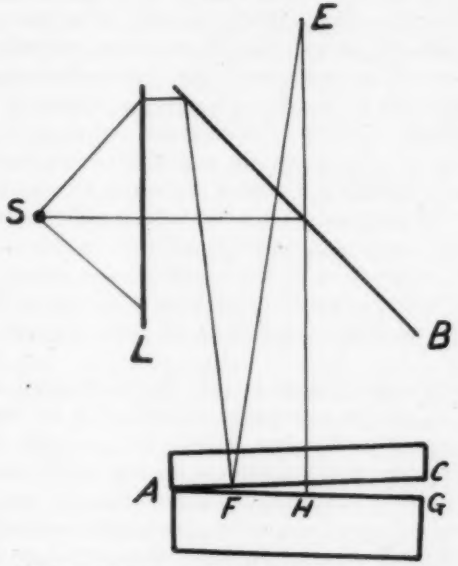
$$\therefore S = .60\ X + .045\ t_K$$

Here a comparison of (d) and (e) with (b) and (c) shows that sighting along the fringes obliquely increases the error arising from straight fringes at about the same rate as when sighting across them, insofar as the part arising from the actual deviation X from planeness is concerned; while the error arising from the thickness t_K of the film is six times as large in (d) as in (b) and ten times as large in (e) as in (c). For surfaces anywhere near

true, X is likely to be small as compared with the thickness of the film. In which case these examples show that sighting along the fringes may go a long way toward straightening them and should therefore be especially avoided.

An improvement over the customary apparatus for testing planeness of a surface would be the addition of a thin plate of glass B set at an angle of 45° to the perpendicular EH from the

FIG. 8.



Satisfactory arrangement for illuminating test surface.

eye to the surface (Fig. 8), but even then care should be taken to use only the small portion of the film near the foot of the perpendicular EH if a high degree of accuracy is desired, as this apparatus eliminates only the larger errors illustrated by examples (b), (c), and (d) and (e) above. In fact, if ϵ is to be kept less than one per cent., the ratio d/P should not exceed $^1/_7$, as may be determined from equation (7).

BUREAU OF STANDARDS,
WASHINGTON, D. C.

A COLORIMETER OPERATING ON THE SUBTRACTIVE PRINCIPLE.

BY

L. A. JONES.

DURING the recent war, the writer was engaged in the conduct of research work dealing with the question of marine camouflage. In connection with this, it became necessary to make measurements of the color of the sky, just above the horizon, under various conditions of weather through the regions in which vessels were subject to attack by submarines. At that time no instrument suitable for this work was available on the market, and it was necessary, therefore, to design and construct special apparatus suitable for the purpose. After carefully considering the requirements of such apparatus, and the materials readily available for use in their construction, it was decided that a colorimeter utilizing the subtractive principle of color mixture offered the greatest promise as to quickness of construction, portability, and simplicity of operation.

Since such an instrument is well adapted to many commercial uses, such as the measurement of the color of fabrics, wall coverings, papers, paint, glass, liquids, etc., it seems desirable to present at this time a description of the instrument and the principle upon which it operates. In considering the various means of measuring and specifying color, the conclusion that the monochromatic method[1] of color analysis offers the most satisfactory solution seems unavoidable. This follows from a consideration of the fundamental nature of color and the factors necessary for its specification. When radiant energy is incident upon the retina of the normal eye, the sensation of light is produced. This sensation may be said to consist of two factors, brightness and color, the former being dependent upon the intensity and the latter upon the quality of the incident radiation. The quality of the radiation may be specified by stating its wave-length, in case radiation of but one frequency is present; or, in case it is composed of a mixture of frequencies, by stating the wave-length and intensity

[1] Nutting, P. G.: *Bull. Bur. Stand.*, Vol. 9, 1913, p. 1.

of each of the component elements. This constitutes complete objective specification of the quality of the radiation and hence of the color. The retina, however, being a synthetic rather than analytic receiving organ, does not recognize the individual component part of the radiation as such, but receives the mixed radiation at a single stimulus producing a single sensation. This sensation, as stated previously, may be specified by two factors, brightness and color, and the latter factor may also be split into two components, hue and saturation. Hue refers to the position in the spectrum of the dominant quality, while purity expresses the proximity of the color to the condition of monochromatism. The factors necessary for the complete specification of the sensation resulting from the action of radiant energy upon the retina are brightness, hue, and saturation.

By the monochromatic method of color analysis these factors are measured, and a specification of color in terms of the various subjective factors is obtained.

Monochromatic analysers, while they must be regarded as most suitable for the measurement of color in absolute terms, unfortunately are somewhat complicated in design, and up to the present time no satisfactory portable model suitable for field use has been developed. The three-color additive method of color mixture has been applied to the measurement of color and several different types of instruments employing this fundamental principle have been produced. Such instruments involve the use of either of three arbitrary color screens (red, green, and blue) so arranged that the intensity of the light transmitted by each can be varied at the will of the operator, this transmitted light being subsequently mixed to match the unknown, or of three fairly narrow bands suitably chosen from the spectrum which are mixed in the proportions to match the unknown. Three-color additive instruments of the spectral type are particularly complicated and objectionable as field instruments, while other instruments of this class due to structural peculiarities lack portability and simplicity of operation. While the subtractive instrument is subject to some of these objections, it is free from many of them, especially from the necessity for motor-driven parts and adjustable slits, which in order to function properly are expensive to construct.

The subtractive instrument described in the paper has been

found very satisfactory in field work, and in view of its portability, simplicity of operation, and freedom from the necessity of delicate adjustment of parts should be found very useful in many branches of commercial industry. The color wedges which constitute the essential part of the instrument are reproducible with considerable precision and under the conditions existing in the instrument they show practically no fading over long periods of time. For many classes of work the specification of color in terms of the constants of the instrument is quite sufficient, but if it be desired to express color in terms of the fundamental factors (hue and saturation) it is only necessary to calibrate the instrument by comparing it with the absolute instrument, the monochromatic analyzer.

It may be well at this point to explain more fully the meaning of the terms "additive mixture" and "subtractive mixture." While these terms have been used to a considerable extent, especially in connection with various processes of color photography, they may not be commonly understood. Perhaps the best way of explaining these terms is by the citation of concrete examples. Suppose, for instance, two projecting machines are mounted side by side and each illuminate the same screen surface. Now in front of one of the projecting lenses let a green filter be placed, while before the other is placed a red filter. One projector acting alone would illuminate the screen with green light while the other acting alone would illuminate the screen with red light. The two acting simultaneously result in a screen illumination which is yellow, and this may be taken as a typical example of the additive mixtures of red and green.

Now assume that only one projecting machine is used and that both the red and green filters are placed in front of the projecting lens. The light which reaches the screen must pass through both filters, but since the green filter transmits no red light and the red filter transmits none of the light passed by the green filter, the screen is not illuminated and we may say that this subtractive mixture of red and green produces darkness or black.

In order to obtain a yellow screen illuminated by the subtractive method, it is only necessary to place in front of the projecting lens a filter which absorbs the blue component of the sensibly white light emitted by the light source, the yellow in this

case being obtained by the subtraction of the blue from the white light of the projecting beam. Suppose now that in front of the projecting lens of one of the lanterns is placed a blue-green filter and also a yellow filter. The screen will now be illuminated by green light, the red component originally present in the white light of the source being subtracted by the blue-green (that is, minus red) filter, while the blue component is subtracted by the yellow filter(that is, the minus blue), the resultant screen illumination being due to the light transmitted by both filters, this being the green component.

Thus in the case of additive mixture the resulting color is built up by mixing lights of various colors, while in the case of the subtractive method the desired color is arrived at by subtracting certain parts from the light used as a source of illumination. For

FIG. 1.

Diagram of optical parts.

a color mixing device which is designed to match all possible colors by the additive method, a properly selected set of filters transmitting the primary colors—that is, red, green, and blue-violet—are used, but if the subtractive method is to be employed, the three primary filters cannot be used since they are practically mutually exclusive and it is necessary to adopt the three colors complementary to the primaries, namely minus red, that is blue-green; minus blue, that is, yellow; and minus green, which is magenta or purple.

In Fig. 1 is presented a diagram showing the arrangement of the essential parts of the subtractive colorimeter. The lens L_1L_2 forms an image of the surface whose color is to be measured in the plane of the photometer tube C. This image is examined by means of the lens L_3L_4, and the eye-piece system E. The lens system L_1L_2 is adjustable so that any surface at a distance greater than 3 feet from the photometer cube may be focused in the

cube plane. On the axis perpendicular to and intersecting the line of sight at the dividing line of the photometer cube is placed the light source S with a diffusing screen at G as indicated. A filter, F, reduces the color of the light illuminating the photometer cube from the source S to a subjective match with noon sunlight. Four gelatine wedges are placed as indicated by W, each wedge being adjustable in a horizontal direction so that it may be inserted to any extent or withdrawn completely from the path of the beam of light from the lamp S. A set of neutral gray filters is provided

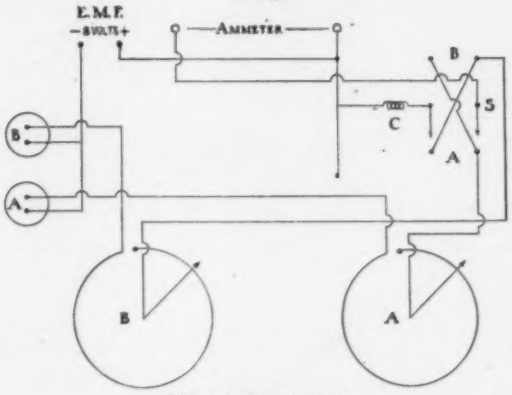
FIG. 2.

Instrument mounted for field work.

at G′ in order that the intensity of the light from the object may be controlled so that it shall fall within the range of the instrument. The colored wedges used are as indicated in the figure, one being minus green, one minus blue, and one minus red, while the fourth is neutral tint and is provided in order that an intensity balance may be obtained. In making a measurement of color, the wedges are so adjusted that the light transmitted by them matches that from the object under consideration. By using three wedges of the complementary colors as indicated, that is, minus green, which transmits the red and blue regions; minus blue, which transmits the red and green; and minus red which

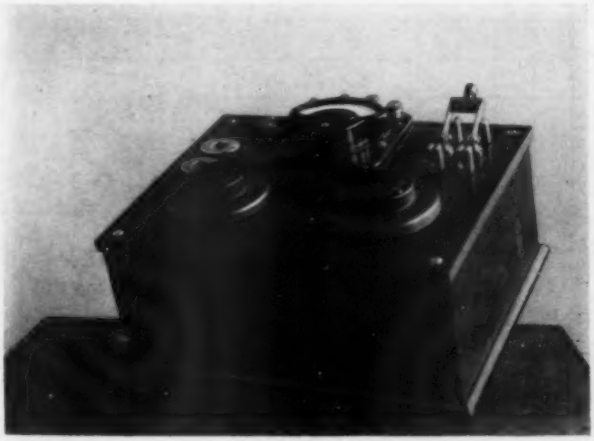
transmits the green and blue, any color whatever can be matched by proper adjustment. The position of each wedge is indicated by

FIG. 3.



Wiring diagram of control.

FIG. 4.

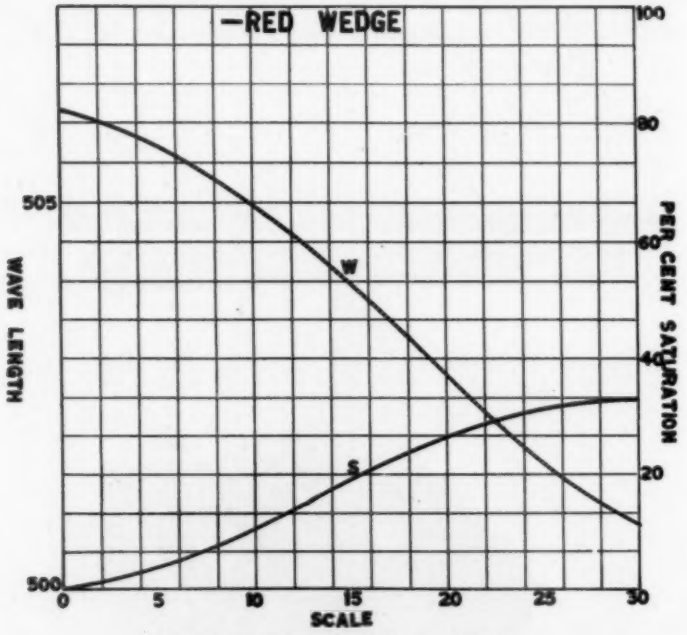


Control box.

a pointer attached to the wedge frame and reading upon a graduated scale. A photograph of the finished instrument is shown in Fig. 2.

With this instrument color measurement is made by matching light from the object with light from the source S and transmitted by the wedges. It is necessary therefore that the lamp S be operated under fixed conditions in order that the emitted light shall be of constant color. A control box is therefore provided containing the necessary variable resistance and an indicating in-

FIG. 5.

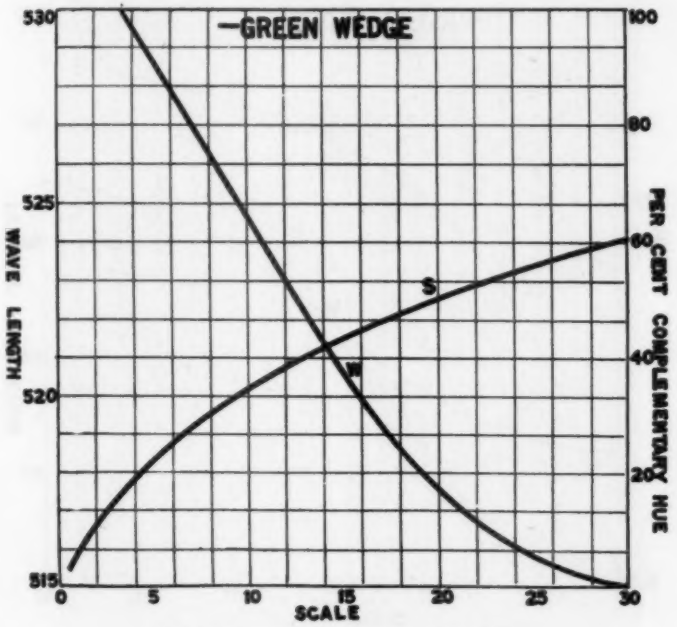


Hue and saturation curves for minus red wedge.

strument. Since the quality and intensity of the light emitted by a lamp run at a fixed current may change with the age of the lamp, it is necessary to provide a means of checking this lamp from time to time and of finding the current at which a renewal lamp must be operated. For this purpose a standard lamp is provided which may be attached to the instrument in front of the lens system L_1L_2. This standard lamp is seasoned and the current determined at which it must be operated in order that the light

emitted by it when screened with the proper filter, which is mounted as an integral part of the standard lamp house, shall match noon sunlight in color. In checking the working lamp against the standard, it is necessary to operate both lamps under fixed conditions. The control box is, therefore, provided with two connections so that both lamps may be operated simul-

FIG. 6.



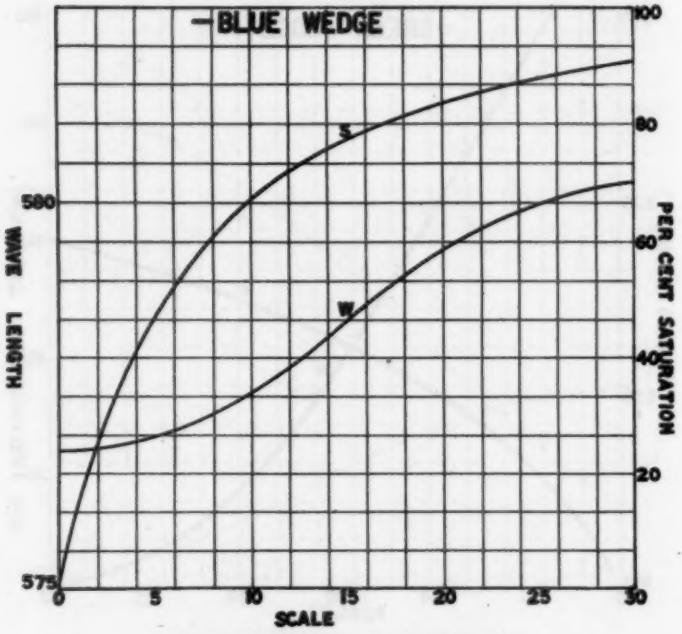
Hue and saturation curves for minus green wedge.

taneously and the current in either read on the ammeter, the necessary change in the connection being made by a double pole double throw switch. A diagram of the electrical connection of the control box is shown in Fig. 3, and a photograph of the control box in Fig. 4.

The three colored wedges used in the instrument have been analyzed on the monochromatic analyzer, and the results are given in Figs. 5, 6, and 7. The abscissæ values are the scale reading

numbers, while the ordinates at the left of each figure (marked wave-length) are the wave-lengths of the dominant hue. The ordinate scale at the right of these figures gives the values of saturation in per cent. The curve marked W in each case refers to the wave-length of the dominant hue while that marked S is the curve of saturation. The dye concentration used in the

FIG. 7.



Hue and saturation curves for minus blue wedge.

manufacture of these wedges is so adjusted as to give wedges of such gradient that the scale of the instrument will be fairly open for the reading of colors of low saturation, and at the same time permit the reading of high saturation colors. With the wedges actually used, no colors other than those existing in the spectrum have been found of such saturation as to be beyond the range of the instrument.

While some difficulty was experienced with the first wedges

manufactured for this purpose, in that they were not as stable as could be desired, this has been very largely overcome, methods having been worked out for properly stabilizing the dyes used. As an illustration of the stability obtained, it might be mentioned

FIG. 8.

Attachment for holding transparent samples.

that one of these wedges was exposed to daylight continuously for over a month at the end of which time no perceptible fading had occurred. When it is considered that fading is due largely to the extreme blue and ultra-violet light, and that this component

is much stronger relatively in daylight than in the light from the tungsten lamp used in this instrument, it will be seen that there is little danger of fading. The wedges are enclosed in a dust-proof

FIG. 9.

Attachment for holding reflecting samples.

housing so as to be completely protected from injury. While the instrument was designed primarily for the measurement of the color of objects at some distance, it can be easily adapted to other

purposes. Special attachments have, therefore, been built for holding samples of materials to be measured. One of these shown in Fig. 8 is designed for holding transparent solids such as colored glass or filters of celluloid or gelatine. The sample being placed in the slot, the attachment is fastened to the objective end of the instrument by means of the threaded ring above. A lamp for providing the necessary illumination of the sample is mounted in the housing below, in front of which is carried an opal glass diffusing screen and filter of proper quality to reduce the light to sunlight quality.

A second attachment for use in measuring the color of reflecting surfaces such as fabrics, paper, etc., is shown in Fig. 9. This also is attached to the objective end of the instrument by a threaded ring. The lamp providing the necessary illumination is mounted in the housing. The sample to be measured is held in contact with the upper right-hand surface by means of a spring clip not shown in the figure. The illumination on the sample is from a disk of diffusing glass which subtends a relatively large angle at the point of observation on the sample. The mean angle of incidence of this illumination is 45° while the sample is preserved normally. A third attachment for the measurement of liquids is provided, the liquid in question being placed in a flat-bottomed glass tube which can be easily inserted and removed from its holder. Only one lamp housing for the illumination of the samples being measured is provided with each instrument, this being so constructed that it can be attached to any one of the three different fixtures provided for samples of different character.

EASTMAN KODAK COMPANY,
ROCHESTER, N. Y.,
October 29, 1920.

TRANSMISSION AND REFRACTION DATA ON STANDARD LENS AND PRISM MATERIAL WITH SPECIAL REFERENCE TO INFRA-RED SPECTRORADIOMETRY.*

BY
W. W. COBLENTZ.

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I. INTRODUCTION.†

THIS paper gives exact data on the spectral transparency and in particular, the refractivity of materials which are useful for prisms and lenses for spectroradiometers.

The data on refractive indices were taken from smooth curves, drawn through values which were collected from various sources and reduced to a common temperature.

It is important, especially in work of the highest precision (such as, for example, the determination of the constant of spectral radiation), to use the most precise instruments and optical data available. It is, therefore, relevant to discuss very briefly some recent designs of optical instruments suitable for spectroradiometry.

The pioneering investigation of the infra-red refractive indices of a substance dates back to 1886 when Langley determined the dispersion of rock salt to about 5μ. In these determinations a spectrometer having an image forming mirror of long focal length

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† References are given in a classified bibliography at the end of this paper.

was used. In subsequent determinations of the refractive indices of rock salt and of fluorite, the image forming mirror of the spectrometer used by Langley had a focal length of 4 to 4.7 metres. The apparatus was in a large enclosure which could be maintained at a constant temperature. Langley[19] was therefore justified in calling attention to the very high precision attainable "owing, if to no other reason, to the far greater size of the apparatus employed, where size is a most important element of accuracy." Other experimenters,[20, 23, 24] using his methods, but having spectrometer mirrors of only about one-twelfth the focal length, have attempted to produce similar data, which, unfortunately, have been given the widest recognition in tables of physical constants. These published results, especially the older ones, have been very confusing to the writer who, for some years, has been confronted with the task of obtaining reliable refractive indices.

The recent measurements on rock salt [26] and on fluorite [28] by Paschen, when corrected for temperature,[33, 34] are in agreement with Langley's [19] measurements. The numerical values, given in the present paper, have been adopted after a careful study of all the data available.

The Spectroradiometer.—For measuring thermal radiation intensities, in the ultra-violet part of the spectrum, one may use a spectrometer having achromatic lenses of quartz-fluorite. However, the scarcity of clear fluorite, for large sized lenses, makes such apparatus very expensive.

Pflüger [1] used simple lenses of fluorite, 4 cm. in diameter (32 cm. focal length) and a fluorite prism. An inexpensive spectroradiometer of high light-gathering power was made by Coblentz [2] by using simple plano-convex lenses (6 cm. in diameter and 20 cm. focal length) and a prism of quartz. Pfund [5] has described similar apparatus, in which the radiometer is kept in focus automatically, in different parts of the spectrum.

The apparatus may be designed also as an illuminator for separating the visible from the ultra-violet of a source like the sun or a quartz mercury vapor lamp.[4]

For spectroradiometric measurements in the visible spectrum and the infra-red to about 0.8μ we can use a spectrometer with visually achromatized lenses of glass. Here, also, it is desirable to use apparatus having a high light-gathering power, such as one obtains with lenses 6 cm. in diameter and 20 cm. focal length.[2, 3, 4]

A common property of all metals is a low reflectivity in the ultra-violet and in the violet-blue part of the visible spectrum.[15, 16, 17] Furthermore, the spectral reflectivity in the short wave-length is greatly reduced on tarnishing of the metal. Hence concave mirrors of metals have never been used extensively for spectroradiometric measurements in the visible and in the ultra-violet spectrum.

Because of the lack of achromatism (and the opacity of the material) lenses of glass, quartz, fluorite, etc., achromatized for the visible spectrum, have not been used extensively in infra-red spectroradiometric work. Lehmann [46] has described an infra-red spectrograph achromatized for $\lambda = 0.589\mu$ and $\lambda = 1.529\mu$.

A concave mirror is achromatic (also astigmatic) and hence spectrometers with collimating and image-forming mirrors, instead of lenses, have been used almost exclusively for infra-red spectral radiation intensity measurements. In the infra-red spectrum, beyond 2μ most of the metals have a very high reflecting power (90 to 98 per cent.) and concave metal mirrors, or metal-on-glass mirrors, are, therefore, especially useful for infra-red investigations.

Recent designs of spectrometers having collimating and image-forming mirrors are described in papers by Coblentz [6] and by Gorton.[9] Vacuum spectrometers have been described and used by Trowbridge [7] and by McCauley.[8]

In order to obtain the spectral energy distribution of an incandescent substance, it is necessary to correct the observations for absorption of radiation by the mirrors and by the prism. The proper formula for eliminating the absorption in a wedge is given by Paschen,[29] and by Coblentz,[39] who gives also the numerical factors for eliminating the absorption in a wedge of quartz.

It is beyond the scope of this paper to discuss the construction and operation of the instruments (bolometers, thermopiles, etc.) used for measuring the thermal radiation intensities. References are given in the appended Bibliography [10] on "Radiometers."

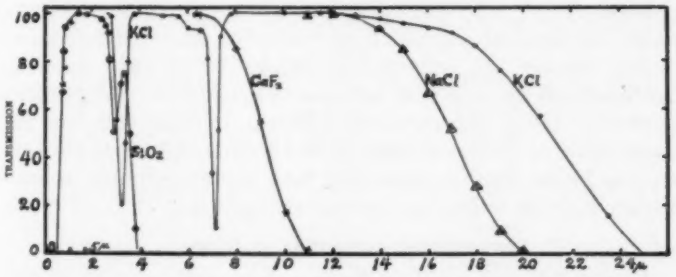
Spectrometer Calibration.—In most spectroradiometric work it is necessary to know the wave-lengths at which the thermal radiation intensities are measured. In the visible spectrum it is an easy matter to note the spectrometer settings for the emission lines of some source (*e.g.*, the mercury arc or helium gas in a

Plücker tube), the wave-lengths of whose emission lines are known. Similarly in the ultra-violet the emission lines of mercury, cadmium, zinc, etc., may be noted with a fluorescent canary glass screen, or radiometrically with a thermophile [1] or bolometer.

The spectrometer circle may be calibrated for wave-lengths in the infra-red spectrum to 1μ, by noting the emission lines [12] of sodium and potassium in a carbon arc; also the emission lines of a quartz mercury vapor lamp, and of helium in a vacuum tube.

Beyond 2μ, where the emission lines are usually weak (except the strong emission band of carbon dioxide at 4.4μ in the bunsen flame) one can calibrate the prism by noting sharp absorption bands,[13, 14] such as, for example, the bands of sylvite, KCl, illustrated in Fig. 1.

FIG. 1.



Transmission of quartz (SiO_2), fluorite (CaF_2), rock salt (NaCl), and sylvite (KCl).

For work requiring great accuracy, the proper method of calibration is by calculating the minimum deviation settings for different wave-lengths, using the refractive indices and the angle of the prism. For this purpose. the yellow sodium lines, or, better, the yellow helium line, $\lambda = 0.5875\mu$, is used as a reference point on the spectrometer circle. The minimum deviation settings for the various infra-red wave-lengths are computed from the corresponding refractive indices, and referred to the yellow helium line as a basis. After this the bolometer or thermopile is adjusted upon the yellow helium line, then on rotating the spectrometer through a certain angle, say $2°$, the corresponding wave-length is, say, 6μ, while a rotation of $4°$ places the bolometer at about 8.7μ in the spectrum of a $60°$ fluorite prism (*loc. cit.*,[6] page 49).

Elimination of Scattered Radiation in Spectral Energy Measurements.—In the design of optical instruments, there are opportunities for great improvement in this respect., Take, for example, the image-forming telescope of a spectrometer. The telescope tube should be large and suitably diaphragmed so that, when the violet end of the spectrum is incident upon the radiometer receiver, the infra-red end of the spectrum cannot be reflected from the side of the tube and impinge upon the receiver. Furthermore, the bevelled edges of the exit slits of the spectrometer should face outwards [18] instead of facing the image-forming lens, as obtains in commercial instruments.

By using suitably constructed optical instruments, the scattered radiation is practically eliminated. What little remains may be obviated by using, before the entrance slit of the spectrometer, a shutter,[22, 5, 18] which is opaque to the region of the spectrum under investigation but which transmits the scattered radiations. In this manner, the scattered radiations are incident upon the radiometer all the time and, hence, do not affect the energy measurements. Using a spectrometer which is provided with slits and diaphragms, as just mentioned, it has been found [4] that the scattered radiation was immeasurable, and hence negligible in comparison with the intensities under investigation.

II. OPTICAL CONSTANTS OF GLASS.

In the ultra-violet end of the spectrum, ordinary crown glass is transparent to about 0.3μ, while the flint-silicate glasses absorb strongly throughout the blue and violet end of the spectrum.

In the infra-red spectrum, all glasses [38, 40] begin to absorb at about 2μ, and, for a thickness of 1 cm., they are practically opaque to radiations of wave-length greater than 3μ. Glasses containing traces of iron impurities have an absorption band at 1μ.

The refractive indices of various glasses have been determined by Rubens.[20] He determined the refractive indices also of water, xylol, benzol, etc. However, in view of the fact that the refractive indices depend upon the composition of the glass, no refraction data are given in this paper. Practically no infra-red work is being done with glass prisms.

III. OPTICAL CONSTANTS OF CARBON DISULFID.

Carbon disulfid is quite transparent in the infra-red. In the region to 3μ, Rubens [20] found an absorption of only 5 to 7 per

cent. for a 1 cm. thickness. Beyond 4μ there are a number of very large absorption bands.[36]

As illustrated in Fig. 3, carbon disulfid has a very much larger dispersion than quartz, etc., in the region of 0.5 to 2μ, and hence is especially adapted for certain fields of spectroradiometry.

The infra-red refractive indices of carbon disulfid were determined by Rubens.[20] Those in the visible and in the ultra-violet were determined by Flatow.[32] Rubens's values of the infra-red refractive indices are given in Table I.

TABLE I.

Indices of Refraction of Carbon Disulfid in Air at 15° C. (Rubens).

Wave-lengths μ =0.001 mm.	Refractive Index, n	Log n
0.434μ	1.6784	0.2248955
0.485	1.6550	.2187980
0.590	1.6307	.2123741
0.656	1.6217	.2099705
0.777	1.6104	.2069338
0.823	1.6077	.2062050
0.873	1.6049	.2054480
0.931	1.6025	.2047980
0.999	1.6000	.2041200
1.073	1.5978	.2035224
1.164	1.5960	.2030329
1.270	1.5940	.2024883
1.396	1.5923	.2020249
1.552	1.5905	.2015337
1.745	1.5888	.2010692
1.998	1.5872	.2006317

IV. OPTICAL CONSTANTS OF QUARTZ.

Quartz is one of the most useful materials for prisms. It is extremely transparent to ultra-violet radiations. Pflüger [41] found a transmission of 94 per cent. at 0.222μ and 67 per cent. at 0.186μ, for a sample of crystalline quartz, 1 cm. in thickness. Some samples of amorphous quartz have been found to be more opaque than crystalline quartz; but this may be the result of contamination in melting.

The infra-red transmission of quartz has been determined by various observers. A characteristic absorption band occurs at about 2.95μ. A sample 1 cm. in thickness is practically opaque [38] to radiations of wave-length greater than 4μ (see Fig. 1).

The absorption, reflection and dispersion constants of quartz are given in a paper by Coblentz,[39] who determined the transmis-

sion of samples 3 cm. in thickness. The paper gives also factors for eliminating the absorption in a quartz prism.

In the short wave-lengths the refractive indices of quartz have been determined by Martens.[31] In the infra-red there are important determinations by Rubens,[21, 23] Carvallo,[35] and Paschen.[27] Carvallo's data extend to 2.2μ and in the region of 1.45 to 1.8μ they are slightly lower (by several units in the fifth decimal place) than three determinations made by Paschen. In this region of the spectrum, the data must therefore be considered uncertain with the doubt in favor of Carvallo's data. This uncertainty affects Warburg's [43] determination of the spectral radiation constant by perhaps 0.2 to 0.4 per cent.

The refractive indices (ordinary ray) of quartz at 18° C. are given in Table II. They are taken from a graph of sufficient size to permit reading the data to 1 or 2 units in the fifth decimal place. In many cases the values agree exactly with Carvallo's measurements. Paschen's data may be recognized by the fact that his wave-lengths are given to the fifth decimal place.

V. OPTICAL CONSTANTS OF FLUORITE.

Fluorite is very transparent to radiations of wave-lengths extending from 0.2μ to 10μ (see Fig. 1). Pflüger [41] found a transmission of 86 per cent. at 0.23μ and 70 per cent. at 0.186μ, for a sample 1 cm. in thickness. Lyman [42] examined fluorites from various sources, and of various colors, and found that they are opaque to radiation of wave-lengths less than about 0.12μ. Coblentz [38] examined green fluorites with a view of determining their suitability for prisms. He found numerous sharp absorption bands, in the infra-red, which would render such material unsuitable for prisms.

The refractive indices of fluorite have been determined by various observers,[21, 28] and repeatedly by Paschen.[23, 24, 25, 28] Applying temperature coefficients of refraction,[33, 34] it is found that Paschen's determinations, especially the latest ones [28] which were obtained with an improved spectrometer, coincide with the dispersion curve of fluorite determined, to 3.5μ, by Langley.[19] Beyond 4μ the dispersion of fluorite is much larger than at 1.5 to 2μ and there is better agreement among the various determinations of the refractive indices. Furthermore, slight deviations have less effect upon spectral radiation measurements.

TABLE II.

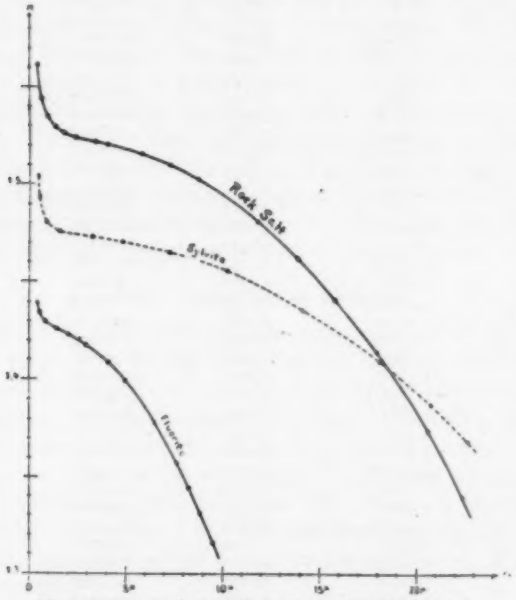
Indices of Refraction of Quartz in Air at 18° C. (Carvallo, Paschen).

Wave-lengths $\mu = 0.001$ mm.	Refractive Index, n	Log n
0.54609μ	1.54617	0.1892573
.58758	.54430	.1887317
.58932	.54424	.1887148
.61577	.54323	.1884306
.66784	.54154	.1879548
.6731	.54139	.1879126
.6950	.54078	.1877404
.70654	.54048	.1876561
.72817	.53995	.1875066
.7711	.53895	.1872245
.8007	.53834	.1870523
.8325	.53773	.1868801
.84467	.53752	.1868208
.8671	.53712	.1867078
.9047	.53649	.1865298
.9460	.53583	.1863432
.9914	.53514	.1861480
1.01406	.53486	.1860405
1.0417	.53442	.1859443
1.08304	.53390	.1857970
1.0973	.53366	.1857291
1.12882	.53328	.1856214
1.1592	.53283	.1854940
1.17864	.53263	.1854373
1.2288	.53192	.1852361
1.3070	.53090	.1849468
1.3195	.53076	.1849071
1.3685	.53011	.1847226
1.3958	.52977	.1846162
1.4219	.52942	.1845268
1.47330	.52879	.1843478
1.4792	.52865	.1843081
1.4972	.52843	.1842427
1.52961	.52800	.1841234
1.5414	.52782	.1840722
1.6087	.52687	.1837921
1.6146	.52680	.1837822
1.6815	.52585	.1835118
1.7487	.52486	.1832300
1.76796	.52462	.1831616
1.8487	.52335	.1827997
1.9457	.52184	.1823690
2.0531	.52005	.1818579
2.06262	.51991	.1818178
2.1719	.51799	.1812689
2.35728	.51449	.1802664
2.3840	.51400	.1801259
2.4810	.51200	.1795518
2.575	.51100	.1792645
2.65194	.50824	.1784704
2.79927	.50474	.1774614
3.09393	.49703	.1752305

In Table III, the refractive indices of fluorite to 3.5μ are taken from the smooth curve published by Langley.[19] In many cases Paschen's original wave-lengths are retained. As already mentioned, the corresponding refractive indices, when corrected for temperature of the prism, fall exactly upon Langley's curve of refractive indices.

Beyond 3.5μ the refractive indices are taken from the smooth

FIG. 2.



Dispersion curves of rock salt, sylvite and fluorite (Rubens).

curve (extended from 3μ) through the various determinations of Paschen [25] and Rubens.[20] All these data are reduced to 20° C.

Langley's data are referred to the "A line," $\lambda = 0.7604\mu$. The most convenient reference point for adjusting a spectro-radiometer in the spectrum is the yellow helium line, $\lambda = 0.58758\mu$. Until recently, when Paschen [28] determined the refractive index of this line, there has been some uncertainty in infra-red spectral radiation measurements [44] requiring the highest accuracy. An error of 5″ (or $n = 3 \times 10^{-5}$) in the determination of this refrac-

TABLE III.

Indices of Refraction of Fluorite in Air at 20° C. (Langley, Paschen, Rubens).

Wave-lengths $\mu = 0.001$ mm.	Refractive Index, n	Log n
0.48615μHβ	1.43704	0.1574695
.58758 He	.43388	.1565120
.58932 Na	.43384	.1564995
.65630 Hα	.43249	.1560916
.68671	.43200	.1559430
.72818 He	.43143	.1557601
.76653 K	.43093	.1556184
.88400	.42980	.1552753
1.0140 Hg	.42884	.1549835
1.08304 He	.42843	.1548589
1.1000	.42834	.1548316
1.1786	.42789	.1546948
1.250	.42752	.1545822
1.3756	.42689	.1543905
1.4733	.42642	.1542474
1.5715	.42596	.1541073
1.650	.42558	.1539916
1.7680	.42502	.1538210
1.8400	.42468	.1537173
1.8688 He	.42454	.1536747
1.900	.42439	.1536274
1.9153	.42431	.1536046
1.9644	.42407	.1535313
2.0582 He	.42360	.1533880
2.0626	.42357	.1533789
2.1608	.42306	.1532232
2.250	.42258	.1530766
2.3573	.42198	.1528936
2.450	.42143	.1527255
2.5537	.42080	.1525329
2.6519	.42018	.1523460
2.700	.41988	.1522517
2.750	.41956	.1521538
2.800	.41923	.1520528
2.850	.41890	.1519518
2.9466	.41823	.1517467
3.0500	.41750	.1515231
3.0980	.41714	.1514128
3.2413	.41610	.1510939
3.4000	.41487	.1507134
3.5359	.41376	.1503788
3.8306	.41119	.1495855
4.000	.40963	.1491051
4.1252	.40847	.1487476
4.2500	.40722	.1483620
4.4000	.40568	.1478864
4.6000	.40357	.1472341
4.7146	.40233	.1468502
4.8000	.40130	.1465311
5.000	.39908	.1458426
5.3036	.39522	.1446427
5.8932	.38712	.1421141
6.4825	.37824	.1393312
7.0718	.36805	.1361020
7.6612	.35675	.1324998
8.2505	.34440	.1285290
8.8398	.33075	.1240965
9.4291	.31605	.1192724

tive index affects the constant of spectral radiation by 0.3 per cent.

The dispersion curve of fluorite is illustrated in Figs. 2 and 3 (from Rubens').

In the infra-red, the variation of the refractive index of fluorite [34] with temperature decreases slowly with wave-lengths. At 1μ the coefficient of variation amounts to about $\Delta n = 0.000\,012$ and at 6.5μ it amounts to about $\Delta n = 0.000\,009$, for 1° rise in temperature.

VI. OPTICAL CONSTANTS OF ROCK SALT.

Rock salt is uniformly transparent from 0.2μ in the extreme ultra-violet [41] to 12μ in the infra-red [23] (see Fig. 1). In the region of 15μ the absorption increases rapidly. A plate of rock salt 1 cm. in thickness is completely opaque [22] to radiation of wave-lengths greater than 20μ. The refractive indices of rock salt have been determined in the short wave-lengths by Martens,[39, 31] and in the infra-red by Langley,[16] by Rubens,[21, 22] and by Paschen.[20] In the region of 1 to 3μ there is considerable disagreement among the older determinations. However, the recent work of Paschen [20] is in excellent agreement with Langley's measurements which are, without doubt, very accurately determined.

The infra-red refractive indices of rock salt, at 20°, are given in Table IV. The first part of the table, to 5μ, consists principally of Langley's (and Paschen's corrected for temperature) measurements as read from the smooth curve (*loc. cit.*,[19] p. 235, plate XXIX). Beyond 5μ, to 16μ, the refractive indices are principally Paschen's measurements, corrected for temperature;[34] also some of Rubens' measurements and several interpolated values.

The temperature coefficient of refraction of rock salt [19, 33, 34] decreases slowly with wave-length; amounting to about $\Delta n = 0.000\,038$ at 1μ and $\Delta n = 0.000\,025$ at 9μ, for 1° rise in temperature.

The general outline of the dispersion curve of rock salt is illustrated in Fig. 2 (from Rubens).

VII. OPTICAL CONSTANTS OF SYLVITE.

Of all the substances which are otherwise suitable for prisms, sylvite, KCl, is transparent throughout the greatest part of the infra-red spectrum. A plate 1 cm in thickness transmits [22] radia-

TABLE IV.

Indices of Refraction of Rock Salt in Air at 20° C. (Langley, Paschen, Rubens).

Wave-lengths $\mu = 0.001$ mm.	Refractive Index, n	Log n
0.5893μ	1.54427	0.1887232
.6400	.54141	.1879182
.6874	.53930	.1873233
.7604	.53682	.1866230
.7858	.53607	.1864110
.8835	.53395	.1858112
.9033	.53361	.1857149
.9724	.53253	.1854090
1.0084	.53206	.1852758
1.0540	.53153	.1851255
1.0810	.53123	.1850404
1.1058	.53098	.1849695
1.1420	.53063	.1848702
1.1786	.53031	.1847794
1.2016	.53014	.1847312
1.2604	.52971	.1846091
1.3126	.52937	.1845126
1.4874	.52845	.1842512
1.5552	.52815	.1841660
1.6368	.52781	.1840693
1.6848	.52764	.1840238
1.7670	.52736	.1839414
2.0736	.52649	.1836960
2.1824	.52621	.1836142
2.2464	.52606	.1835716
2.3560	.52579	.1834947
2.6505	.52512	.1833040
2.9466	.52466	.1831730
3.2736	.52371	.1829024
3.5359	.52312	.1827341
3.6288	.52286	.1826600
3.8192	.52238	.1825231
4.1230	.52156	.1822891
4.7120	.51979	.1817836
5.0092	.51883	.1825092
5.3009	.51790	.1812432
5.8932	.51593	.1806792
6.4825	.51347	.1799738
6.80	.51200	.1795518
7.0718	.51093	.1792443
7.22	.51020	.1790345
7.59	.50850	.1785453
7.6611	.50822	.1784647
7.9558	.50665	.1780124
8.04	.6064	.1779403
8.8398	.50192	.1766468
9.00	.50100	.1763807
9.50	.49980	.1760333
10.0184	.49462	.1745308
11.7864	.48171	.1707632
12.50	.47568	.1689922
12.9650	.47160	.1677898
13.50	.4666	.1663117
14.1436	.46044	.1644837
14.7330	.45427	.1626450
15.3223	.44743	.1605976
15.9116	.44090	.1586338
14.93	.4149	.1507257
20.57	.3735	.1378287
22.3	.3403	.1272020

tions to 24μ (see Fig. 1). In the region of 5μ to 10μ the dispersion is small. Furthermore, there are sharp absorption [11, 13] bands at 3.18μ and 7.08μ. Hence, sylvite is the most useful for investigations in the region of the spectrum extending from 10 to 20μ.

In the short wave-lengths the refractive indices of sylvite have

TABLE V.

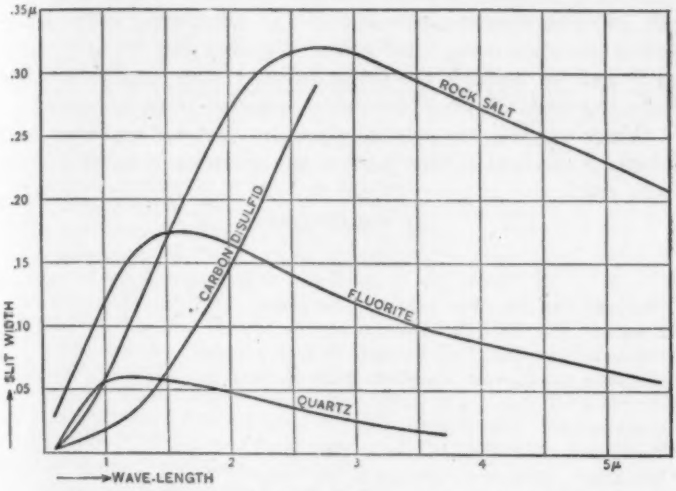
Indices of Refraction of Sylvite in Air at 15° C.

Wave-lengths μ = 0.001 mm.	Refractive Index, n	Log n
0.5893μ	1.49044	0.1733145
.656	.48721	.1723723
.7858	.48328	.1712232
.845	.48230	.1709361
.884	.48142	.1706782
.9822	.48008	.1702862
1.003	.47985	.1702177
1.1786	.47831	.1697655
1.584	.4765	.1692335
1.7680	.47595	.1690717
2.3573	.47475	.1687184
2.9466	.47388	.1684621
3.5359	.47305	.1682164
4.125	.47215	.1679521
4.7146	.47112	.1676481
5.3039	.47001	.1673202
5.50	.46962	.1672050
5.8932	.46880	.1669627
6.50	.46750	.1665781
7.00	.46625	.1662080
7.661	.46450	.1656894
8.00	.46350	.1653927
8.2505	.46272	.1651642
8.8398	.46086	.1646086
9.500	.45857	.1639273
10.0184	.45672	.1633760
10.500	.45475	.1627883
11.00	.45263	.1621550
11.786	.44919	.1611253
12.50	.44570	.1600782
12.965	.44346	.1594048
14.144	.43722	.1575232
15.00	.4320	.1559430
15.912	.42617	.1541713
16.50	.42230	.1529912
17.00	.41885	.1519365
17.680	.41403	.1504586
18.10	.4108	.1494655
19.00	.4031	.1470886
20.00	.3939	.1442316
20.60	.3882	.1424520
22.5	.3692	.1364669

been determined by Martens.[21] In the infra-red we have various determinations by Rubens[22] (with Nichols and with Trowbridge) by Trowbridge,[45] and by Paschen.[26]

The infra-red refractive indices of sylvite are given in Table V. They are read from the smooth curve (practically Paschen's curve) drawn through the various determinations, all of which are in close agreement, except at 9 to 11μ where the older determinations do not agree very well with Paschen's data.

FIG. 3.



Comparative dispersion of prisms at different wave-lengths in the spectrum.

The temperature coefficient of refraction of sylvite observed by Liebreich[34] decreases from

$$\Delta n = 0.0000364 \text{ at } \lambda = 0.589\mu \text{ to}$$

$$\Delta n = 0.0000031 \text{ at } \lambda = 8.85\mu.$$

VIII. SUMMARY; COMPARISON OF DISPERSIVE MATERIALS.

In Fig. 3 is given the width that a radiometer receiver of 4′ of arc, subtends in wave-lengths, in different parts of the spectrum produced by prisms of carbon disulfid, quartz, fluorite and rock salt. These data are required for reducing the spectral energy distribution from the prismatic into the normal spectrum.[6]

From these curves it is evident that, in the region of 0.5 to 1.5μ, a carbon disulfid prism is the most useful for producing a large dispersion.

The next best prism material is quartz, which is the most useful in the region of the spectrum extending from the visible to 2.8μ in the infra-red. Beyond this point, a quartz prism is too opaque for practical work.

From the standpoint of dispersion and transparency, a fluorite prism is the most useful in the region of 2μ to 9μ. However, the material is difficult to obtain and the next best substance is rock salt, which permits measurements to 14μ, when using a 60° prism, and to 16μ when using a 30° prism. By enclosing the spectrometer [14] and by keeping the prism covered when not in use, the faces of a rock salt prism are easily protected from moisture.

There are but few sylvite prisms in existence and their usefulness is confined to that part of the spectrum extending from 10 to 20μ.

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BUREAU OF STANDARDS,
WASHINGTON, D. C.

A NEW STUDY OF THE LEUCOSCOPE AND ITS APPLICATION TO PYROMETRY.*

BY

IRWIN G. PRIEST.

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APPENDIX II. BIBLIOGRAPHY.

* Published by permission of the Director, Bureau of Standards. This paper is an amplification and extension of a paper under similar title by Priest and Foote, presented orally at the New York meeting of the Optical Society of America, February 27, 1920, but not printed. For lack of time, Dr. Foote has been obliged to abandon the original plan of completing this work as a joint investigation. The present author desires to express, however, his hearty appreciation of Dr. Foote's assistance and advice and also of the lively interest he has taken in the work. The author is also indebted to Dr. K. S. Gibson, Messrs. C. M. Blackburn, H. J. McNicholas and Mark Malamphy for assistance. Most of the figures have been prepared by Mr. Chester L. Snow and Miss Gertrude Clemens.

INTRODUCTION.†

1. History of the Leucoscope.

"Books are sepulchres of thought;
The dead laurels of the dead
Rustle for a moment only,
Like withered leaves in lonely
Churchyards at some passing tread."—*Longfellow.*

THIS paper deals with a new study of an old optical instrument, practically unknown to contemporary science—the leucoscope. The invention of this instrument is commonly attributed to Helmholtz [1] (about 1878–1882), but it appears that a very similar instrument under another name, "Farbenmesser," was really practically used by Rose in the diagnosis of color-blindness at an earlier date (1863).[2] The name, "leucoscope" (*Greek:* white + view), was apparently coined by Kitao,[3] a pupil of Helmholtz, in his doctor's thesis, *Zur Farbenlehre*, 1878. From 1878 to 1888 a number of papers dealing with this instrument were published by Helmholtz's pupils, Kitao, Koenig and Brodhun.[4]

The potentialities of the instrument as a means of investigation in two distinct fields, vision and the character of the emission of light sources (in modern terms, spectral distribution, color temperature) were clearly pointed out by these early investigators. Koenig, particularly, made a rather extensive series of leucoscopic observations [5] on various light sources, including the

† Prospective readers of this paper should first familiarize themselves with a paper by Koenig, "Das Leucoscope . . ." *Ann. der Phy. und Chem.*, **17**, pp. 990–1008, year 1882. A complete bibliography is given in Appendix II to the present paper; but an acquaintance with this one paper by Koenig will be sufficient to give the reader an understanding of the subject, and prepare him to read the present paper intelligently.

[1] Cf. papers by Koenig and Brodhun (see Appendix II, this paper) and Webster's International Dictionary, 1910 ed.

[2] Rose's instrument could not, however, have been used by trichromatic observers as the leucoscope is, because he prescribes a fixed thickness of quartz of only 5 mm. (*Archiv für path. Anat.* **28**, p. 36), whereas from about two to four times this thickness is necessary to make use of the leucoscope principle. (See Section 1–2 below.)

[3] There appears to be some doubt and controversy as to the relative contributions of Kitao, and his master, Helmholtz, in the original design and naming of the instrument. (Cf. last section of Kitao's second paper. For reference, see Appendix II.)

[4] See bibliography, Appendix II to this paper.

[5] *Ann. der Phy. und Chem.*, **17**, pp. 1003–1008; year 1882.

just then newly introduced carbon filament lamps [6] of Swan and Edison; and tabulated the latter results as a function of current and candlepower. Notwithstanding these early promises of its utility in two important fields of scientific investigation, the instrument appears to have fallen into almost complete oblivion since the appearance of Brodhun's paper in 1888.[7] So far as can be found, no later papers dealing with it have been published. There is indeed occasional casual reference to it in works dealing with vision;[8] but these merely serve to indicate that no practical use is made of the instrument, and indeed that the authors themselves have but slight acquaintance with it. So far as I can find, recent and contemporary authorities [9] on pyrometry, spectral distribution and color temperature make absolutely no mention of this instrument; and it is apparently quite unknown to present-day pyrometry. It is not indexed and apparently not mentioned in many of the best known standard works of reference on physics, optics, chromatics and pyrometry.[10] In declining to quote price on a leucoscope in reply to a recent request, the original makers [11] state that there never was any demand for the instrument and that

[6] "The carbon filament lamp was developed about the year 1878 . . ."—Solomon: "Electric Lamps," p. 95; London, 1908.

"In 1879, Swan exhibited a lamp with a filament of carbon in a vacuum bulb, and followed this by various improvements."—New Int. Enc. (1918 Ed.), Vol. 21, p. 715.

"The Edison incandescent lamp was first exhibited in 1879 . . . ."—New Int. Enc. (1918 Ed.), Vol. 7, p. 599.

On the 20th of October, 1880, Sir Joseph Wilson Swan gave at Newcastle the first public exhibition on a large scale of electric lighting by means of glow lamps—Enc. Brit. (11th Ed., 1911), Vol. 26, p. 179, under "Swan, Sir Joseph Wilson."

[7] The author is indebted to his former associate, Mr. P. V. Wells, for having first directed his attention to the leucoscope. Mr. Wells happened to notice Koenig's paper in the *Annalen der Physik* while searching the literature on another subject.

[8] Norris and Oliver: "System of Diseases of the Eye," Vol. II ("Detection of Color Blindness," Wm. Thompson), p. 347. Tscherning: "Physiologic Optics," Eng. trans. by Weiland, p. 270; The Keystone Press, Philadelphia, 1904.

[9] For example, G. K. Burgess, Block, Hyde, H. E. Ives, L. A. Jones, P. D. Foote. Cf. also Appendix II to this paper.

[10] Cf. Appendix II.

[11] Schmidt and Haensch, Cf. *Zeit. für Instk.*, 3, p. 20, Jan., 1883.

they have not made one for about twenty years. The leucoscope has been buried in the uncut pages of scientific papers.

2. Design and Essential Principles of the Leucoscope.

The essential principle of the leucoscope design is this: Two juxtaposed images of a rectangular aperture produced by double refraction are viewed through a nicol prism and a variable thickness of crystalline quartz, the nicol being between the eye and the quartz, and the optic axis of the latter being coincident with the line of sight.[12]

To a normal observer, with "white" light illumination, the two images appear, in general, in complementary colors, of unequal brilliance. If another nicol be interposed between the doubly refracting part (calcite rhomb) and the light source, it may be set so as to equalize the brilliance of the two images, leaving them still complementary in color.

Experimental spectroscopic analysis, as well as theoretical consideration based on the rotatory dispersion of the quartz, shows that the spectra of both images are banded[13] and, in particular:

(1) The bands become narrower and more closely spaced as the thickness of quartz is increased.

(2) The system of bands moves through the spectrum as the ocular nicol is rotated.

(3) The bright bands of one image coincide with the dark bands of the other, and conversely; that is, the wavelengths of the maximum and minimum intensity in the two images respectively coincide. The two images are physically complementary in the sense that the light absent from one is in the other.

Trichromatic observers find the following phenomena:

(1) For all thicknesses of quartz greater than about 9 mm., there are found certain positions of the ocular nicol (one in each quadrant), for which both images are very pale (very nearly

[12] For diagrams of design, consult any one of the following papers: Koenig: *Ann. der Phy. und Chem.*, 17, p. 990; Koenig: *Zeit. für Instk.*, 3, p. 20; *Brodhun*: *Ann. der Phy. und Chem.*, 34, p. 897.

[13] Cf. Appendix I and Figs. 13 and 14, this paper.

white) and, accordingly, very nearly color matched. One may be a very pale blue; the other a very pale yellow; neither may be recognized as more reddish than the other. *This is the criterion for the leucoscope setting* which may be made with considerable accuracy for thicknesses of quartz not much in excess of 20 mm.

(2) For great thicknesses of quartz both images are very pale for *all* positions of the ocular nicol; consequently, the setting by the above criterion cannot be made accurately.

3. Summary of Conclusions from Early Work.

The findings of Kitao, Koenig and Brodhun, insofar as they bear on our present interest in the leucoscope, may be summarized as follows:[14]

(1) The setting of the ocular nicol ("leucoscope reading"), by a trichromatic observer, for the condition of closest approach to color match of the two images (neither image reddish with respect to the other)-depends upon:

a. The thickness of quartz.

b. The observer.

c. The spectral distribution of energy of the source (color temperature).

(2) Color-blind as well as normal trichromatic observers may make a setting, their criterion being *perfect* rather than approximate color match; and, indeed, they can make the match with a much smaller quartz thickness than the trichromatic observer. They also find the setting to depend upon the quartz thickness and the source of light.[15]

(3) There may or may not be a systematic difference in the settings made by the two eyes of the same observer.[16]

(4) The personal equation in the leucoscope reading cannot be explained in terms of the Young-Helmholtz theory alone.[17]

(5) The personal equation in the leucoscope reading can be explained by assuming individual differences in the relative visi-

[14] In some cases the obvious modern interpretation of the conclusions of the original papers has been restated in modern terms.

[15] Brodhun: See Appendix II for reference.

[16] Kitao: *Zur Farbenlehre*, pp. 29–31.

[17] Kitao: *Zur Farbenlehre*, pp. 6 and 21.

bility of radiant power. (Modern interpretation of Kitao's conclusions.[18])

(6) The leucoscope is a valuable instrument for the diagnosis of color-blindness.[19]

(7) The leucoscope is a valuable instrument for studying the spectral distribution or color temperature of incandescent solids. (*Modern interpretation of the results of Koenig and Kitao.*[20])

(8) For a constant light source and the same observer, the rotation of the ocular nicol is approximately but not *exactly* a linear function of the thickness of quartz.[21] (Koenig emphasizes the fact that the relation is *not linear;* but on plotting his data,[22] it is found that the departure from a linear relation is *not much* greater than the experimental uncertainty.)

(9) Twenty millimetres of quartz is a suitable standard to use for comparative observations on different light sources.[23]

4. Limitations of Early Work.

It will be noticed, in the section above, that, in order to present them cogently, it has been necessary to restate or interpret in modern terms the original conclusions of Kitao and Koenig. This is because concepts now current were not well formulated; and quantitative data now available did not exist when their papers were published. They could not correlate and formulate their results to the best advantage because of a lack of fundamental data and fundamental concepts of two kinds, viz.:

(1) Visibility of radiant power.[24]

(2) The spectral distribution of energy as a function of temperature—temperature scale for the complete radiator ("black body") and incandescent solids—color temperature.[25] The very

[18] *Zur Farbenlehre*, p. 21, and *Ab. Tok. Univ.*, **12**, pp. 30–31.

[19] Rose.

Koenig: *Centb. für Prak. Augenheilk.*, **8**, pp. 375–377. Brodhun: *Ann. der Phy. und Chem.*, **34**, p. 918.

[20] Koenig: *Ann. der Phy. und Chem.*, **17**, pp. 1003–1008. Kitao: *Abh. Tokio University No. 12*, pp. 34–58.

[21] Koenig: *Ann. der Phy. und Chem.*, **17**, pp. 1001–1002.

[22] *Ann. der Phy. und Chem.*, **17**, p. 1001.

[23] Koenig: *Ann. der Phy. und Chem.*, **17**, p. 1004.

[24] Koenig's determination of visibility, the earliest that is now given any consideration, was not made until about 1890.

[25] Wien's distribution law was published in 1896; Rayleigh's, in 1900; Planck's, in 1900. The scale of color temperature has been established only in very recent years by Hyde and others.

terms in which the results could have been most simply and instructively stated were lacking. It is interesting to notice how this lack of data and concepts prevented the consummation of this early work, and how when these data and concepts became available, the work had apparently been forgotten.

5. Purpose and Scope of the Present Paper.

The purpose of the present paper is to give an introduction to a modern treatment of the leucoscope in terms of knowledge now available. The experimental basis consists of leucoscopic observations on light sources of known temperature by three observers of previously known visibility,[26] and not "color-blind." These observations were made under the following conditions and circumstances[27]:

(1) The criterion for the leucoscope setting was that adopted by Koenig.[28] viz.: An approximate match of color quality (hue and saturation) is made *such that neither field can be recognized as reddish relative to the other.* For the lower temperatures, this results in a nearly or quite perfect match of color quality; for the higher temperatures, one field is very pale blue, the other, very pale yellow. No attempt was made to match brilliance.

(2) One standard thickness of quartz, 20.000 mm.. as recommended by Koenig[29] for the comparison of different sources was used in all observations. (The correctness of this thickness was checked by comparing its measured rotation for homogeneous light with Lowry's tables.[30])

(3) Temperatures are referred to the color temperature scale of Hyde;[31] and are expressed in degrees Kelvin (absolute tem-

[26] I. G. Priest, P. D. Foote and H. J. McNicholas. Visibility by Coblentz and Emerson, *B. S. Sci. Pap.* 303.

[27] For further details, see also II below.

[28] *Ann. der Phy. und Chem.*, **17**, p. 999.

[29] *Ann. der Phy. und Chem.*, **17**, p. 1004.

[30] *Phil. Trans. Roy. Soc. A.*, **212**, p. 287; year 1912–13.

[31] Only color temperatures between about 1700° and 2400° K are referable *directly* to Hyde's scale as established by the Nela Research Laboratory. Light of spectral distribution corresponding to temperatures above 2400° K is obtained directly from gas-filled lamps and by rotatory dispersion as explained under II–2 below. Temperatures below 1700° K are from a small black body. See also II–2 below.

perature), except in one figure, where degrees Centigrade are used.

(4) Each observer used only his right eye.

(5) One observer made many repeated observations at various times over a period of several months so as to test the constancy of reading. Another repeated his first calibration after a period of several months. The third made calibrations on two successive days.

(6) The observer's eye was protected from extraneous light by a closely fitting eye-shade.

The primary data are presented in the form of calibration curves of leucoscope reading against temperature, arranged so as to show the personal equation and its degree of constancy with time.

These data are discussed with regard to (1) precision, (2) the personal equation, (3) the variation of the personal equation with time, (4) possible use of the leucoscope as a pyrometer.

Two new fundamental laws of the leucoscope are then derived from these data, and stated in terms relating the leucoscope reading to the spectral distribution of light, i.e., *to the spectral distribution of energy of the light source and the observer's relative visibility of radiant power.*

As illustrative of the use of the instrument and without attaching any permanent value or importance to them (because of their preliminary nature), leucoscopic determinations of the color temperature of several sources are given, as well as a series of determinations of the apparent color temperature of sunlight at the earth's surface showing its diurnal variation.

II. APPARATUS AND METHODS USED IN THE PRESENT INVESTIGATION.

1. *The Arons Chromoscope and Its Use as a Leucoscope.*

No leucoscope originally designed as such was available for this investigation. However, the Arons chromoscope[32] is so designed that it may be used to make leucoscopic observations (with some disadvantages noted below). The essential parts of this instrument as used in this investigation are shown in Fig. 1 and explained in the accompanying key.

[32] Leo Arons. *Ann. der Phy.* (4), **39**, pp. 545–568; 1912.

In using this instrument as a leucoscope the Lummer-Brodhun cube (LB) is removed and the analyzing nicol (A) is replaced by the Wollaston prism (W). The principal optical parts, in order from the eye, are then: (1) the observing telescope, (2) the Wollaston prism (W), (3) the quartz plates ($Q_I - Q_7$), and (4) the nicol, (P). The quartz plates, $Q_I - Q_{IV}$, do not function in the leucoscope, and are removed except that one of them is used in obtaining light corresponding to very high temperatures as explained below. Rotation of nicol, P'', relative to nicol P', serves to adjust the field to a comfortable working brilliance.

One sees, on looking into the instrument, two circular images due to the Wollaston prism. These images are each about 3° in diameter and overlap about one-quarter the diameter of either. It will be noticed that this arrangement is the reverse of the order of parts in the original leucoscope in that the element producing the double image (the Wollaston prism, W) lies between the eye and the quartz instead of between the quartz and the source.

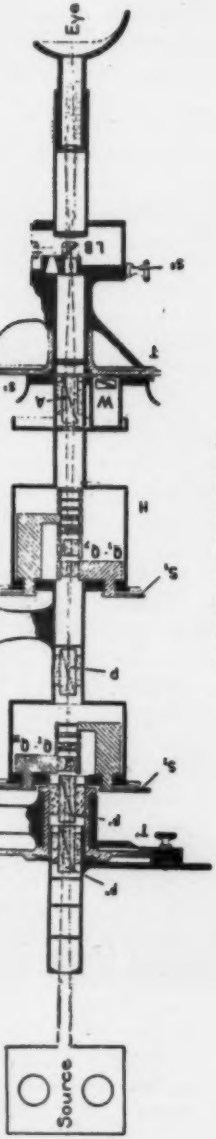
This results in the disadvantage that the images rotate as the Wollaston prism is rotated to make the leucoscopic match. A few observations indicate a possible small systematic difference between readings in opposite quadrants, that is, with the positions of the images reversed—the whole field of observation turned through 180°. All readings reported in this paper were made in the same quadrant and are therefore comparable, although their absolute significance may be questioned; that is, we may expect the same observer to obtain slightly different values with a properly designed instrument.

Another disadvantage is the overlapping of the images. This would be a very serious matter if brilliance (intensity) matches were involved, but is not very troublesome in making the matches of color quality, which is all that is done. These disadvantages, although not very serious, were only tolerated because it was not practicable to make promptly any better arrangement for this preliminary work. *It may probably be assumed that the precision and accuracy with a properly designed instrument would be better than that found in this preliminary investigation.*[33]

Leucoscopic readings, by the criterion of Koenig described above, were made by rotating the Wollaston prism with the

[33] It is now planned to have a new model instrument constructed in the Bureau of Standards instrument shop.

FIG. 1.



PART OF ARONS CHRONOSCOPE.
(From *Ann. der Phy.* (4) 39. p. 547.)
Key.

LB—Lummer-Brodhun cube, *removed in the present use of the instrument.* A—Nicol prism, *removed and replaced by W in the present use of the instrument.* W—Wollaston prism, *used in place of A* and rotating with the divided circle T. (In this instrument W and A are mounted on a slide so that *either* may be brought into the axis of the instrument at will.) Q–Q—Quarts plates. *In the present work, all of these plates except three of thicknesses respectively 8, 8 and 4 mm. were removed.* P—Nicol prism in fixed position. Q–Q′—Quarts plates, *not used as part of leucoscope,* but one of them (1 mm.) used in connection with P and P′ to obtain light of spectral distribution corresponding to very high temperatures, as explained in the text. P′–P″—Nicol prism. Rotation of P″ relative to P′ serves to vary absolute brilliance of both images.

divided circle, T (Fig. 1), in the same direction as the rotation of the plane of polarization by the quartz, angles being measured from zero for the extinction position of the extraordinary image

FIG. 2.

Assembled apparatus.

with all quartz removed. This angle is designated as the "leucoscope reading." (In reducing the results, care has been taken to correct for the small "zero error" of the circle.)

2. Pyrometric Calibration—Temperature Scales.

The pyrometric calibration has been made in part by pointing the instrument into a black body at measured temperatures and in part by pointing it at a magnesia surface illuminated by lamps at known color temperature. Care was taken to obtain a uniform field in each case. A single determination usually consisted of five observations. (In some cases only three, and in others, ten.)

The earliest quantitative observations of any reliability or importance were made on a small black body of the type used by Fairchild in the Bureau of Standards' pyrometric laboratory,[34] and kindly loaned and operated for this purpose by Dr. Foote. Temperatures were read by Dr. Foote by means of a disappearing filament optical pyrometer immediately before and after each leucoscopic determination; and are estimated by him to be reliable to about 5° C. However, this estimate of accuracy applies only to the measured brightness temperature for wavelength 650 millimicrons. We do not know how closely the small black body in question approximates to an ideal complete radiator, and therefore cannot state how closely these measured brightness temperatures should agree with color temperatures. With this source, a temperature range from about 800° to 1600° C (1173°–1873° K) was obtained (Fig. 5). To obtain higher temperatures standard incandescent filament lamps were used, either directly or by an intermediate comparison source, and the observations made on the light reflected from a magnesium oxide or carbonate surface illuminated by the lamp.

A point at 2360° K was obtained by means of a vacuum tungsten lamp operated at a voltage previously determined to give a color match with a standard acetylene flame assumed to have this color temperature, as indicated by the most recent findings of Coblentz as well as those of Hyde, Forsythe and Cady.[35]

[34] This radiator was made of a sillimanite crucible within an outer crucible of alundum, the space between being filled with fused alumina. All sides except the aperture were heated electrically by a heater of platinum-rhodium wire. This furnace was cemented with alundum cement to give practically a one-piece furnace. It was supported on four porcelain legs about 15 cm long; and was freely exposed to the air. The dimensions were: inside diameter, 23 mm; inside length on line of sight, 30 mm; and aperture, 12 mm.

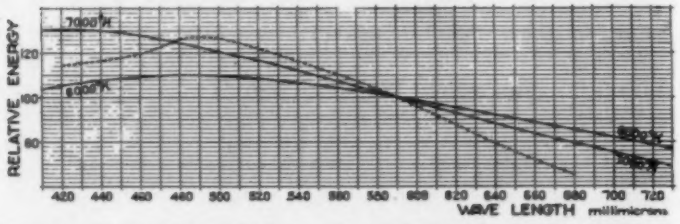
[35] Hyde, Forsythe and Cady: *Phy. Rev.* (2), 13, pp. 157–158, 1919; *Phy. Rev.* (2), 14, p. 379, 1919. Coblentz: *Journ. Frank. Inst.*, pp. 399–401; September, 1919. *B. S. Sci. Pap. 362*, Feb., 1920.

A point at 2830° K was obtained by means of a gas-filled tungsten lamp (B. S. Lamp 1717) of known spectral energy distribution, previously determined radiometrically by Dr. W. W. Coblentz. The color temperature, 2830° K, was derived as follows:

(1) The ratio of energy at wave-length 480 millimicrons to energy at wave-length 680 millimicrons was computed for a complete radiator (Planck's equation $c_2 = 14350$) for various temperatures, and plotted as a function of temperature.

(2) The same ratio for this lamp was found from Coblentz's data, and the corresponding temperature read from the graph just mentioned.

FIG. 3.



Comparison of Spectral Energy Distributions of Complete Radiator at 6000° and 7000° K with Spectral Distributions Obtained by Method of Rotatory Dispersion.
Actual source: B. S. lamp 1716 at 144.1 volts, 22 l.p.w.
Quartz thickness=1.000 mm. ϕ=4.5° (see Appendix I).
Solid curves: complete radiator by Planck's formula (c_2=14350) for 6000° and 7000° K.
Dotted curve: B. S. lamp 1716 at 144.1 volts, modified by rotatory dispersion. Relative energy of lamp $x \sin^2(4.5 - a_\lambda)$ (see Appendix I).

The points at 3000°, 3200°, 4000°, 5000°, and 7000° K were obtained by the artifice of rotatory dispersion, a system consisting of a quartz plate between nicols being inserted between the source and the leucoscope so that the optic axis of the quartz is coincident with the line of sight. The effect is briefly this: Owing to the rotatory dispersion, the nicols and quartz plate constitute, in effect, a selective light filter, the spectral transmission of which is determined by the thickness of the plate and the angle between the principal planes of the nicols.[36] It is pos-

[36] Cf. Arons: *Ann. der Phy.* (4), 33, pp. 810–819, year 1910. Priest: *Phy. Rev.* (2), 10, pp. 208–212, year 1917; *Phy. Rev.* (2), 11, p. 502, year 1918; *Phy. Rev.* (2), 15, pp. 538–539, year 1920; and forthcoming papers "The Application of Rotatory Dispersion to Colorimetry," . . . See also Appendix I, this paper.

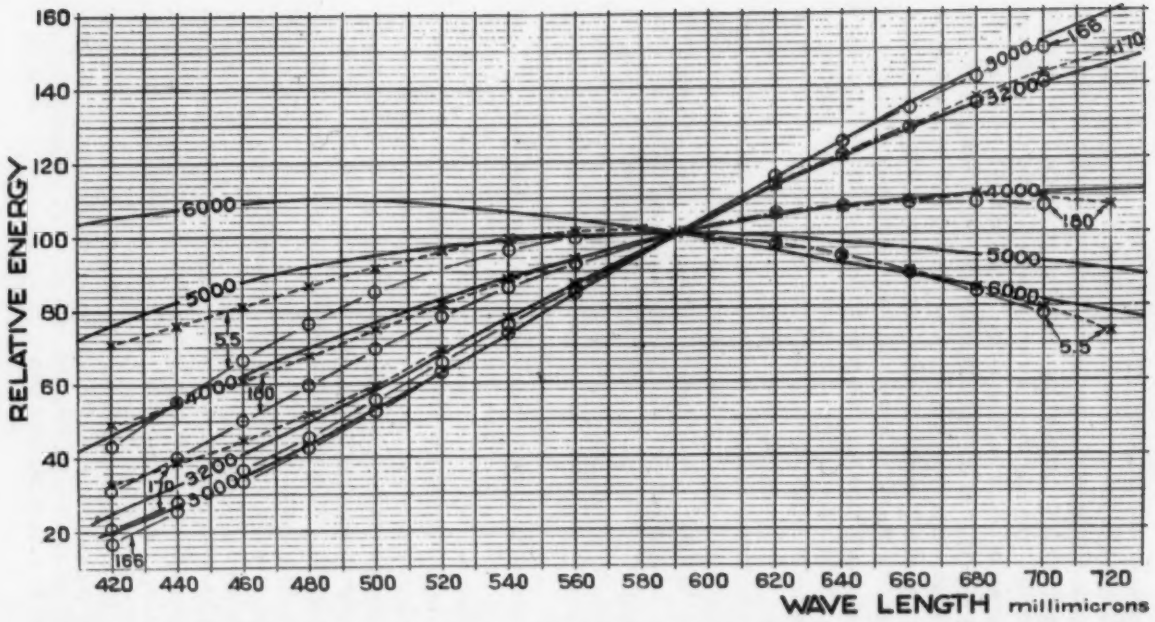
sible to choose this thickness and angle so as to make a *blue filter* which will reduce the actual known spectral distribution of a lamp at operable temperature, approximately to the spectral distribution (by Planck's formula) of a theoretical black body at some assigned high temperature. To accomplish this end in the present instance, use has been made of nicols P′ and P and a 1-mm. quartz plate at Q_I–Q_{IV} (Fig. 1). The complete specifications are recorded in the legends to Fig. 6. The point 7000° K is uncertain because the energy distribution obtained is not strictly that of a black body (Fig. 3). The quantitative significance of the points at 3000°, 3200°, 4000°, and 5000° K may also be questioned because of the uncertainty of spectral distribution of energy in the standard acetylene flame,[37] on which they depend (Cf. legend, Fig. 6). The distribution given by Coblentz and Emerson[38] was first assumed. The resultant spectral distributions have now been recomputed assuming the spectral distribution of a complete radiator at 2360° K (Planck's $c_2 = 14350$) for the acetylene flame. The resultant distributions on both assumptions are compared with the theoretical (Planck's formula, with $c_2 = 14350$) distributions in Fig. 4. On account of these uncertainties, no very definite significance can be ascribed to the calibration above 2830° K. *It will be noticed, however, that, in spite of these circumstances: (1) a smooth calibration curve has been obtained (Fig. 6); (2) the uncertain part is consistent with a reasonable extrapolation of the more certainly established part (Fig. 6); (3) the high temperature calibration is consistent with a reasonable assumption for the color temperature of noon sunlight at the earth's surface* (Cf. Section VI and Fig. 15, below); *(4) the high temperature calibration is consistent with a reasonable assumption for the temperature of the sun itself* (Cf. Sec. VI, below); *(5) the calibration at about 3700° K is consistent with the probable temperature of the electric arc.* (See Sec. IV–5, below.)

In the present state of uncertainty regarding both the spectral distribution of the acetylene flame and the value of Planck's constant, c_2, it does not appear worth while to discuss this ques-

[37] Cf. Hyde, Forsythe and Cady: *Phy. Rev.* (2), 13, pp. 157–158, 1919; *Phy. Rev.* (2), 14, p. 379, 1910. Coblentz: *Jour. Frank. Inst.*, pp. 399–401, Sept., 1919; *B. S. Sci. Pap. No. 362*, Feb., 1920.

[38] *Bull. B. S.*, 13, p. 363; year 1916.

FIG. 4.



Comparison of Spectral Energy Distributions of Complete Radiator with Spectral Distributions Obtained by Method of Rotatory Dispersion.
Actual source at color temperature of acetylene flame. Quarts thickness=1.000 mm.
Solid curves: Complete radiator by Planck's formula (c_1=14350). Numbers attached to these curves indicate temperature in degrees K.
Dotted curves, crosses: Acetylene flame as given by Coblentz and Emerson (Bull. B. S. 13, p. 363), modified by rotatory dispersion.
Dashed curves, circles: Complete radiator at 2360° K, modified by rotatory dispersion.
Numbers attached to dotted and dashed curves indicate values of ϕ in the formula
$\sin^2(\phi - a\lambda)$. (See Appendix I.)

tion further. The calibration curve given (Fig. 6) is probably as significant as can be determined under the present circumstances; and it is considered worth while to publish it as a preliminary roughing out of the complete leucoscope-temperature function for an approximately normal observer for all temperatures between about 1000° and 7000° K.

Probably the most reliable part of the pyrometric calibration is that based on a standard vacuum tungsten lamp supplied by the Nela Research Laboratory,[39] and certified by that laboratory to operate at given color temperatures, between 1700° and 2400° K, when maintained at prescribed voltages. This lamp was used as a standard both directly and indirectly. It was first determined that the selective reflection of a particular block of magnesium carbonate was negligible for this purpose. In the observations of April 1, 1920 (Fig. 7), this magnesium carbonate block being viewed by the leucoscope was illuminated directly by this standard lamp at various voltages, giving a series of color temperatures at which leucoscopic readings were made. This arrangement did not give sufficient light for accurate observations at low temperatures. To overcome this difficulty and to save the standard lamp, the following indirect method was adopted in later work: The standard lamp (at or near S, Fig. 2) illuminated a surface of the magnesium carbonate block placed so (M, Fig. 2) that the reflected light illuminated part of the Arons chromoscope (A, Fig. 2) field by means of the Lummer-Brodhun cube (LB, Fig. 1).[40] All of the quartz plates (Q_I–Q_7 and Q_I–Q_{IV}, Fig. 1) being removed, the other part of the field was illuminated by light reflected through the hole H (Fig. 2), from the magnesium oxide coated interior wall of the box C (Fig. 2), the interior of this box being illuminated by two seasoned vacuum tungsten lamps in parallel. The room was darkened and the block shaded so that no appreciable light other than that from the standard lamp fell upon the magnesium carbonate surface. With this arrangement, the standard lamp was operated at the voltages prescribed to give certain color temperatures (1719, 1849, 1965, 2070, 2164, 2250, 2331, 2409° K). The current in the lamps in the box, C (Fig. 2), was then adjusted to

[39] Letter and Report on Calibration, Nela Research Laboratory to Bureau of Standards, March 8, 1920.

[40] Cf. also Arons: *Ann. der Phy.* (4), 39, p. 545.

give a color match. This calibration of the current in the comparison lamps in terms of color temperature of the standard lamp was repeated many times by the author with different arrangements of the photometric field; and an average calibration curve plotted. It was also checked at 2360° K to within 8° by the means of numerous observations on another Nela standard lamp. Subsequent calibration of the leucoscope was made by observations on the magnesia-coated wall of the box, C, with the comparison lamps in this box, operating at measured currents; and corresponding color temperatures were obtained from the current-temperature calibration curve just mentioned. The observations of August 25–26, 1920, by Foote, McNicholas and Priest (Fig. 7), were made in this way. The chief advantage of this procedure over direct use of the standard lamp is that greater brightness in the leucoscope can be obtained, which is necessary at the low temperatures.

III. EMPIRIC RESULTS OF PYROMETRIC CALIBRATION.

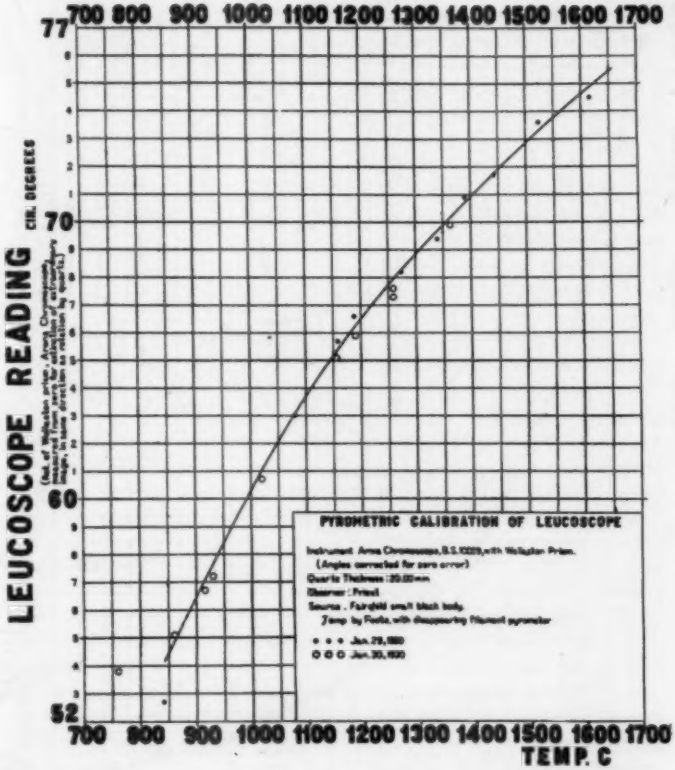
The two calibrations, January 29 and 30, 1920, made with the small black body (about 800–1600° C) and covering the range of industrial furnace temperatures, are shown in Fig. 5. The complete calibration for various temperatures from data obtained between January 29 and February 4, 1920, is shown in Fig. 6. In Fig. 7 are shown:

(1) Calibrations based on the Nela standard lamp as follows:
   - *a.* By Priest, April 1, August 25 and August 26, 1920.
   - *b.* By Foote, April 1, August 25 and August 26, 1920.
   - *c.* By McNicholas, August 25 and August 26, 1920.
   - *d.* Summarized data by Priest at 2000° K. (Mean of all observations, July 8, 9, 12, 16, shown in detail in Table I.)

(2) Summarized previous data by Priest on other sources, obtained between January and August, 1920. (The January-February data have already been shown in Fig. 6, but are reproduced here for the sake of comparison.)

In order to exhibit in detail the precision and the reproducibility of the readings of a practiced observer from time to time, Tables I and II are presented. These data probably represent the most consistent work that can be done by this observer with the present apparatus, but not necessarily the best that could

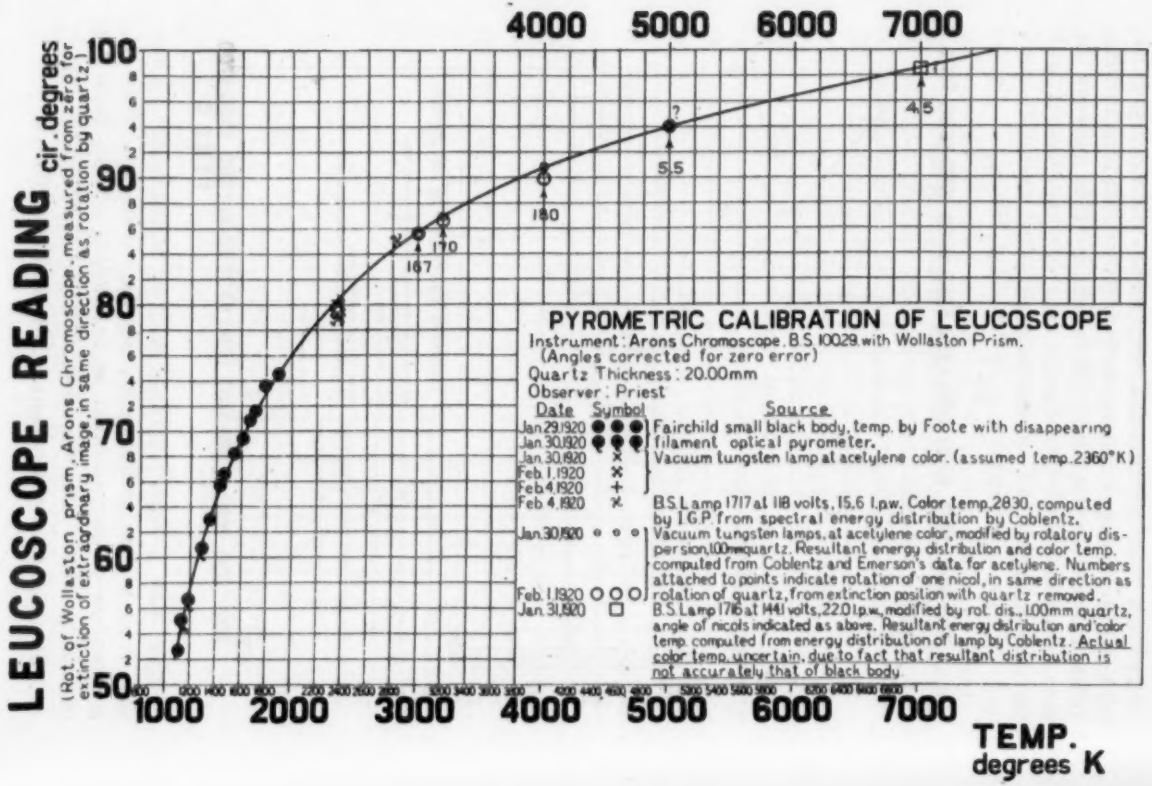
FIG. 5.



be done with a more favorably designed instrument.[41] These data refer to two temperatures, namely, 2000° and 2830° K. Independent of any question as to whether or not these are true temperatures on any scale, they were accurately repro-

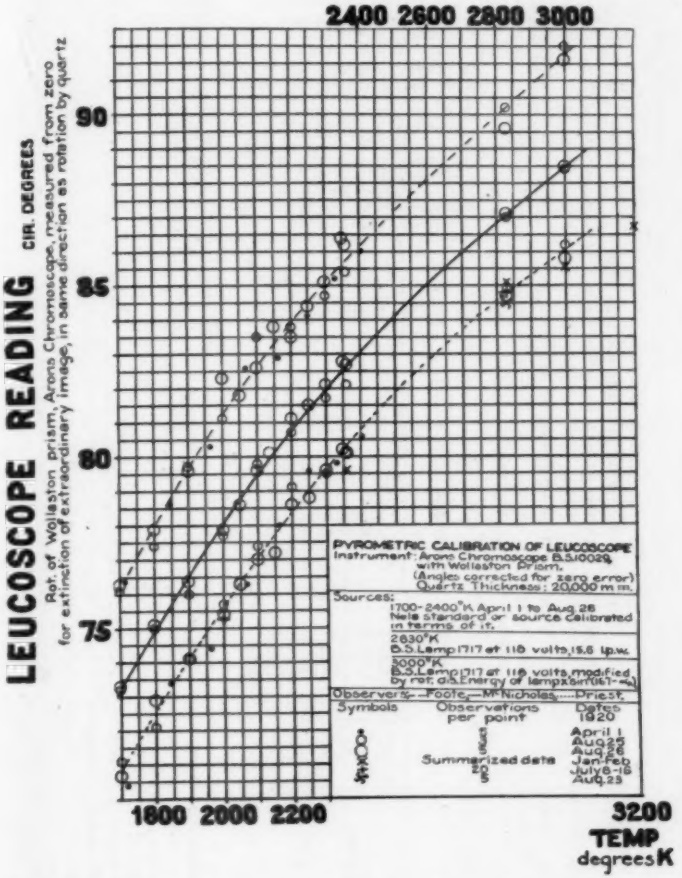
[41] Cf. discussion of disadvantages of instrument under II above.

FIG. 6.


LEUCOSCOPE READING cir. degrees
(Rot. of Wollaston prism, Arons Chromoscope, measured from zero for extinction of extraordinary image, in same direction as rotation by quartz.)
100
90
80
70
60
50
4000
5000
6000
7000
1000
2000
3000
4000
5000
6000
7000
TEMP. degrees K
4.5
5.5
?
180
170
167
PYROMETRIC CALIBRATION OF LEUCOSCOPE
Instrument: Arons Chromoscope. B.S. 10029. with Wollaston Prism.
(Angles corrected for zero error)
Quartz Thickness: 20.00mm
Observer: Priest
Date Symbol Source
Jan 29, 1920 Fairchild small black body, temp. by Foote with disappearing
Jan 30, 1920 filament optical pyrometer.
Jan 30, 1920 Vacuum tungsten lamp at acetylene color. (assumed temp. 2360°K)
Feb 1, 1920
Feb 4, 1920
Feb 4, 1920 B.S. Lamp 1717 at 118 volts, 15.6 l.p.w. Color temp. 2830, computed by I.G.P. from spectral energy distribution by Coblentz.
Jan 30, 1920 Vacuum tungsten lamps, at acetylene color, modified by rotatory dispersion, 1.00mm quartz. Resultant energy distribution and color temp. computed from Coblentz and Emerson's data for acetylene. Numbers attached to points indicate rotation of one nicol, in same direction as rotation of quartz, from extinction position with quartz removed.
Feb 1, 1920
Jan 31, 1920 B.S. Lamp 1716 at 144 volts, 22.0 l.p.w., modified by rot. dis., 1.00mm quartz, angle of nicols indicated as above. Resultant energy distribution and color temp. computed from energy distribution of lamp by Coblentz. Actual color temp. uncertain, due to fact that resultant distribution is not accurately that of black body.

duced from time to time by reproducing the measured currents in the lamps, the whole arrangement of leucoscope, lamps, and accessory apparatus remaining undisturbed during the period

FIG. 7.



of these observations. The consideration of these data thus affords us a pure test of the reproducibility of one observer's readings at fixed points on the temperature scale. (Constancy of the personal equation.)

TABLE I.

Constancy of Leucoscopic Readings with Time.

Temperature—2000° K (referred to Nela Standard Lamp). Observer—Priest.

	Leucoscope reading (corrected for zero error)				Departures of single observations from daily means (without regard to sign)							
Date, 1920	July 8	July 9	July 12	July 16*	July 8		July 9		July 12		July 16*	
Hour	9 : 50 A.M.	11 : 40 A.M.	2 : 20 P.M.	9 : 00 A.M.	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K
Single observations 1	75.1	75.1	75.9	75.1	0.1	8	0.1	8	0.5	40	0.1	8
2	75.1	75.0	75.1	75.7	0.1	8	0.2	16	0.3	24	0.5	40
3	75.0	75.8	75.6	75.1	0.0	0	0.6	48	0.2	16	0.1	8
4	74.7	75.5	75.2	75.0	0.3	24	0.3	24	0.2	16	0.2	16
5	75.0	74.8	75.2	75.1	0.0	0	0.4	32	0.2	16	0.1	8
Mean	75.0	75.2	75.4	75.2		8		26		22		16
Final mean	75.20				14° K							
Daily mean minus final mean	−0.2	0.0	+0.2	0.0								
Temperature equivalents of above differences	16° K	0	16° K	0								
Mean of above temp. "errors" (without sign)	8° K											

* NOTE: Observer not feeling very well, July 16.

TABLE II.

Constancy of Leucoscopic Readings with Time.

Temperature—2830° K (referred to B. S. Lamp 1717 at 118 volts, 15.6 l. p. w.). Observer—Priest.

Date, 1920	Leucoscope reading (corrected for zero error)					Departures of single observations from daily means (without regard to sign)									
	July 8	July 9	July 12	July 16*	Aug. 23†	July 8		July 9		July 12		July 16*		Aug. 23†	
Hour	9 : 05 A.M.	11 : 45 A.M.	2 : 10 P.M.	9 : 10 A.M.	2 : 50 P.M.	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K	Degrees circle	Degrees temp. K
Single observations. 1	84.5	84.8	85.7	84.3	84.0	0.1	12	0.1	12	0.5	60	0.2	24	0.5	60
2	84.3	85.2	84.7	84.9	84.8	.1	12	.3	36	.5	60	.4	48	.3	36
3	84.2	84.5	84.5	84.2	85.3	.2	24	.4	48	.7	84	.3	36	.8	96
4	84.4	84.6	85.9	84.2	84.2	.0	0	.3	36	.7	84	.3	36	.3	36
5	84.6	85.5	85.2	84.8	84.3	.2	24	.6	72	.0	0	.3	36	.2	24
Mean	84.4	84.9	85.2	84.5	84.5		14		41		58		36		50
Final mean	84.7					40° K									
Daily mean minus final mean	−0.3	+0.2	+0.5	−0.2	−0.2										
Temperature equivalents of above differences	−36° K	+24° K	+60° K	−24° K	−24° K										
Mean of above temp. "errors" (without sign)	34° K														

NOTES: * Observer not feeling very well, July 16. † First observations after over one month without any practice.

IV. DISCUSSION OF THE EMPIRIC RESULTS AS TO PYROMETRIC ACCURACY.

1. Precision.

The following estimates of precision of reading (agreement of observations made in rapid succession) are made from the early work done in January and February, 1920. The precision with a properly designed instrument would probably be better.

Temperature degrees K	Average departure of a *single* observation from the mean of a number of observations
1000–2000	10° to 25°
2360	30° to 60°
3000–4000	50° to 100°
4000–5000	100° to 200°

The reader may study the precision at two temperatures (2000° and 2830° K) in detail from Tables I and II, from which the following may be concluded:

Temperature degrees K	Average departure of *single* observation from mean	Maximum departure of *single* observation from mean
2000	8° to 26°	48°
2830	14° to 58°	96°

It will be noticed that the precision falls off notably with increasing temperature. This would appear, however, to characterize measurements of *color temperature* generally, rather than the leucoscope particularly. The reason for it lies in the fact that the quality of color changes much less rapidly with temperature at high temperatures than at low temperatures. The basis of this is apparent in the graphs in Figs. 9 and 10.

2. The Personal Equation.

The pyrometric calibration curves of three different observers will be found in Fig. 7. These three observers represent rather extreme types of visibility among non-colorblind individuals. The visibility curves of these observers taken from Coblentz and Emerson's original plots are shown in Fig. 8. The classification of their relative visibilities according to Coblentz and Emerson [42] is as follows: Foote, subnormal blue; McNicholas, normal; Priest, subnormal red.

A marked personal equation is clearly shown, the differences

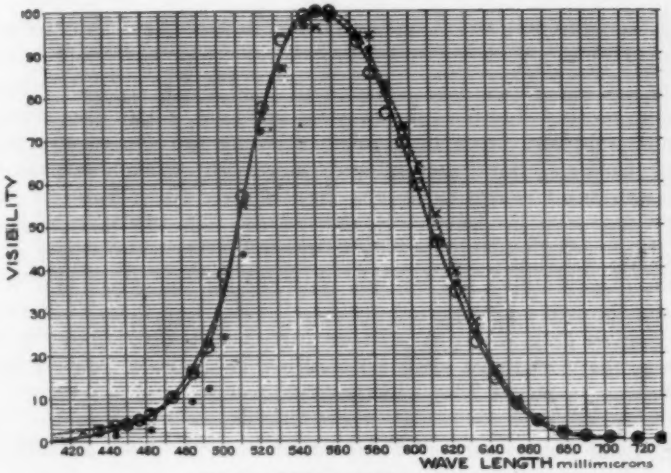
[42] *B. S. Sci. Pap. 303*, pp. 184–185.

between the different observers' readings at all temperatures (1700°–3000° K), being many times the uncertainty of any one observer's reading.[43]

3. The Constancy of the Personal Equation at Different Times.

From the agreement of observations on different days and at different hours as shown in Figs. 5, 6, and 7 and Tables I

FIG. 8.



Relative Visibility of Radiant Power.
Solid curve: Average data adopted as standard in this paper. 400–550 and 660–710 millimicrons, Hyde, Forsythe & Cady, *Astrop. J.* 48, p. 87. 560–650 millimicrons, Ives, *Phil. Mag.* Dec., 1912, p. 859.
Dashed curve: Coblentz and Emerson's average of 125 observers *B. S. Sci. Pap.* 303, p. 219.

Solid circles: Foote	Data by	
Crosses : McNicholas	Coblentz and Emerson	
Open circles: Priest	*B. S. Sci. Pap.* 303, pp. 184–185.	

and II, we conclude that the personal equation is constant, that is, that the change of reading from hour to hour, day to day, and month to month does not exceed the uncertainty indicated by the

[43] Similar calibrations for a number of observers of known visibility have just been completed with the same apparatus by C. M. Blackburn under the author's direction. Time has not yet been available to reduce and fully study these data. They will be published later. In the meantime, we refrain from attempting to make any correlation between the personal equations of visibility and leucoscope reading.

differences between closely successive readings. It will be noticed that the observations on which this conclusion is based extend over several months and include work in both morning and afternoon. Some of the observations were made in a dark room, others in daylight.

Kitao found that previous fatigue by:

(*a*) spectral red, green or violet,
(*b*) spectral red and violet (purple),
or (*c*) "white light,"

did not affect the leucoscope setting; while similar previous fatigue by other homogeneous stimuli destroys the color match and makes *any* setting temporarily *impossible*.[44] In the present investigation, no special tests of the effect of previous fatigue were made; nor were any precautions taken to bring the eye to any particular state; the observers were subject to ordinary laboratory conditions. It will be noticed from the record in Tables I and II that a slight disorder in the observer's health produced no effect in the reading, and it is further to be emphasized that the observer does not lose his criterion for the leucoscopic setting through a long period of disuse. (See Fig. 7 and Table II. Compare data of August 23 with July data, Table II. In Fig. 7, note that Dr. Foote made no observations between April 1 and August 25.)

4. Total Uncertainty of Temperature Reading from a Calibration Curve.

This discussion is based on the data shown in Fig. 7 (Cf. Sec. III above) as follows:

(1) Small black dots, each representing the mean of five immediately successive observations, April 1, 1920, by Foote and Priest.

(2) Small open circles, each representing the mean of three immediately successive observations, August 25, 1920, by Foote, McNicholas, and Priest.

(3) Large open circles, each representing the mean of five immediately successive observations, August 26, 1920, by Foote, McNicholas, and Priest.

[44] *Zur Farbenlehre*, pp. 21–29.

Foote is a skilled observer of long experience in optical pyrometry; but has made scarcely any leucoscopic observations other than those shown in Fig. 7.

McNicholas is a skilled photometrician of exceptional precision; but had made absolutely no leucoscopic observations prior to those shown for August 25.

Priest's experience with the leucoscope dates from the latter part of January, 1920, and is fully shown in this paper.

The point x at temperature 2360° K is not strictly comparable with the data in April and August because different standard sources were used.

Dispensing with any mathematical adjustment, curves judged by appearance to represent these data about as well as possible have been drawn as follows:

Dashed curve, Foote's calibrations, April 1, August 25, 26.

Solid curve, McNicholas' calibrations, August 25, 26.

Dotted curve, Priest's calibrations, April 1, Aug. 25, 26.

The individual readings of the three observers are so far apart that there is no chance of confusing their respective data in the plots.

Taking the departure of each point from the curve, we find the following average and maximum departures:

	Average	Maximum
Foote	25° K	75° K
McNicholas	13°	45°
Priest	20°	58°

Omitting consideration of the points determined by only three observations, that is, considering only those determined by five observations, we find the following maximum departures:

Foote	75° K
McNicholas	30°
Priest	52°

We conclude that,

The average error of a leucoscopic determination of temperature at about 2000° K, based solely on color quality (i.e., paying no attention to equating brilliance) *and derived from five observations by a qualified observer from his own calibration curve is about 15° C, and that the actual error rarely attains 50° C. At lower temperatures, throughout the range of indus-*

trial furnace temperatures, the uncertainty will be less than this. There has been as yet no opportunity to study thoroughly the reproducibility of readings at these lower temperatures.

5. Possible Practical Use of the Leucoscope as a Pyrometer.

It is evident from what has preceded that *the leucoscope may be regarded as a type of optical pyrometer.* Indeed, it has the distinction of being a *strictly* and *purely* optical pyrometer, *requiring no electrical or other accessory apparatus.* It shares this distinction with the sensitive tint pyrometer of Mesuré and Nouel [45] of which it may perhaps be considered a special case. The only essential difference in the design of the two instruments is that Mesuré and Nouel substitute a nicol for the double image rhomb.[46] This results in the observer's seeing only one uniform field instead of two juxtaposed fields to be compared and matched according to a stated definite criterion. (Cf. I–2 above.) The criterion for setting is only the so-called "sensitive tint" which must be carried in the observer's memory, and which changes with temperature. According to LeChatelier, Boudouard and Burgess,[47] as well as the experience of the Pyrometry Section, Bureau of Standards,[48] the Mesuré and Nouel instrument is of little value as a pyrometer. It would appear, *a priori*, highly probable that the leucoscope design would give much better accuracy than that of Mesuré and Nouel because of the more definite criterion it affords. Some data as to the accuracy of leucoscopic temperature measurements have been given just above; *but final judgment on the value of the leucoscope as a pyrometer should not be based on this evidence alone.* It is highly probable that a considerably higher degree of accuracy can be attained with a properly designed instrument (Cf. II–1 above), particularly in

[45] LeChatelier and Boudouard: "High Temperature Measurements," English translation by Burgess, New York, 1901, pages 158–160. Burgess and LeChatelier: "High Temperature Measurements," page 348, New York, 1912.

[46] In the only Mesuré and Nouel instrument which the author has examined, the thickness of quartz is about 11 mm. This would be *sufficient* to use in leucoscopic observations; but is probably not the most favorable thickness (about 20 mm.).

As a pyrometer, the leucoscope might with some reason be called the "duplex or double image sensitive tint pyrometer."

[47] *Loc. cit.*

[48] Information to the author from Dr. P. D. Foote.

the range of industrial furnace temperatures. The author ventures to predict that, within this range, with such an instrument, by making and taking into account the readings for both the quality and brilliance match, temperature determinations from the mean of five observations may be made with an uncertainty of not more than 5 to 10° C. The leucoscope appears to be worthy of careful consideration and study as a pyrometer. If it should prove to possess sufficient accuracy for even a limited number of purposes, its convenience and portability would recommend its wide use. On this score, it is only necessary to say that a complete instrument could be inclosed in a rectangular carrying case not more than 10 × 10 × 30 cm, giving a total weight probably less than 2 or 3 pounds; and that absolutely no electrical or other accessory apparatus would be required for its use.

Without attaching any special importance to them, the following leucoscopic determinations of temperature made by the author on the basis of the calibration curves in this paper are given for comparison with previous data:

Source	Leucoscope Reading (cir. degrees)	Temperature from Calibration	Previous Values	
Kerosene flame (flat)	76.1 (Mean of 20 observations)	2035° K (From Cal. Fig. 7)	2045	Hyde and Forsythe (Jour. Frank. Inst., 183, pp. 353–354).
Paraffin candle	73.9 (Mean of 10 observations)	1890 (From Cal. Fig. 7)	1920	
Crater, carbon arc	89.6 (Mean of 5 observations)	3720 (From Cal. Fig. 6)	3690 3680 3720	Various determinations of black body temperature, by Waidner and Burgess (Bull. B.S., 1, p. 123).

The following possible fields for the use of the leucoscope as a pyrometer suggest themselves:

(1) Temperature measurements of industrial furnaces where the utmost accuracy is not required.

(2) The color grading of incandescent light sources in terms of color temperature.[49]

[49] The author agrees with Hyde and Forsythe (*Jour. Frank. Inst.*, 183, pp. 353–354; 1917) that color temperature affords the most suitable basis for the color grading of illuminants.

(3) Field measurements of the quality of daylight. (Cf. Sec. VI, below.)

(4) The color grading of stars in terms of color temperature. (Subsequent to a more careful calibration for high temperatures.)

V. THE LAWS OF THE LEUCOSCOPE.

1. The Relation between the Leucoscope Reading and the Spectral Distribution of Light from the Source.

The first law derived from the observations recorded in this paper may be stated as follows:

The leucoscope reading is a linear function of the angle through which the plane of polarization of the wave-length of the spectral centre of gravity of the light from the source[50] is rotated by the quartz plate.

This relation has been arrived at by the following procedure:

(1) The spectral luminosity curves of a black body were drawn as shown in Fig. 9, on the basis of data as specified in the legend to that figure.

(2) The wave-lengths of centres of gravity of these curves were determined by a planimeter.

(3) These wave-lengths of centre of gravity were plotted against temperature as shown in Fig. 10.

(4) For selected temperatures (indicated in degrees K by numbers attached to circles in Fig. 11), the angular reading of the leucoscope was read from the calibration curve in Fig. 6 while the wave-length of centre of gravity for the same temperature was read from Fig. 10.

(5) The rotation of the plane of polarization for these latter wave-lengths by 20.000 mm. of quartz was then obtained from a very accurate large scale rotatory dispersion curve based on Lowry's data.[51]

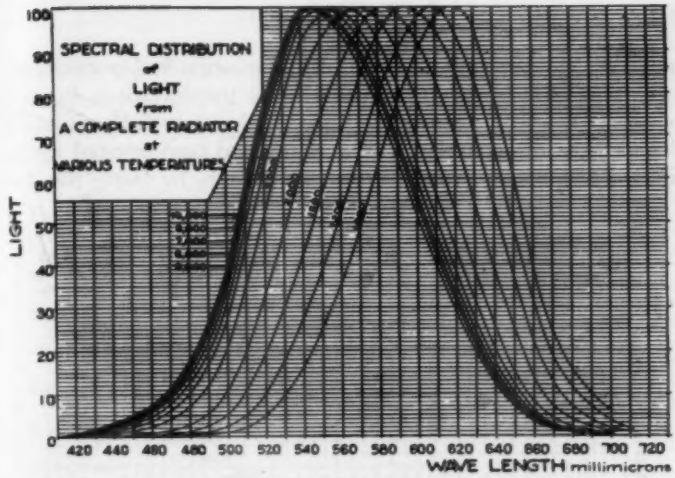
(6) The angular readings of the leucoscope were then plotted against these rotations as shown in Fig. 11.

(7) The locus of these points is found to be accurately a straight line (heavy solid line, Fig. 11) throughout the range

[50] Centre of gravity or so-called "centre of area" of "luminosity curve" of the source.

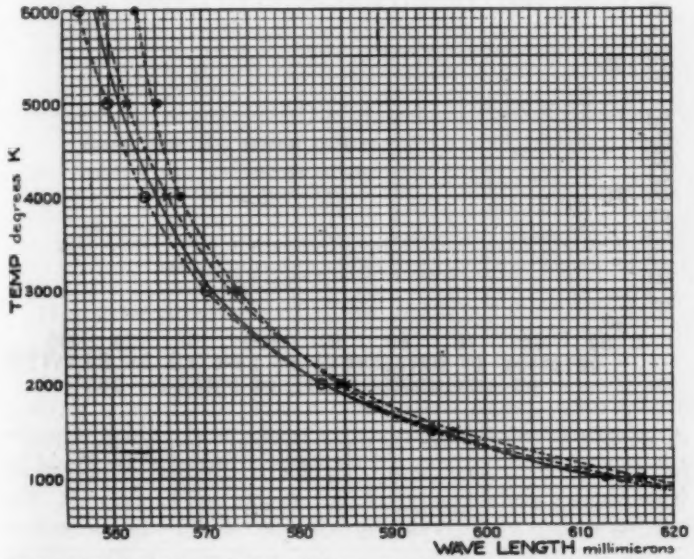
[51] *Phil. Trans. R. S.*, London, A, 212, pp. 288–289; year 1912–13.

FIG. 9.



Spectral Distribution of Light from a Complete Radiator at Various Temperatures. Energy by Planck's formula (c_2=14350).
Visibility: λ, 560–650, H. E. Ives, *Phil. Mag.*, Dec., 1912, p. 859. λ, 410–550 and 660–710, Hyde Forsythe & Cady, *Jour. Frank. Inst.* 48, p. 87.
Numbers attached to curves indicate temperatures in degrees K

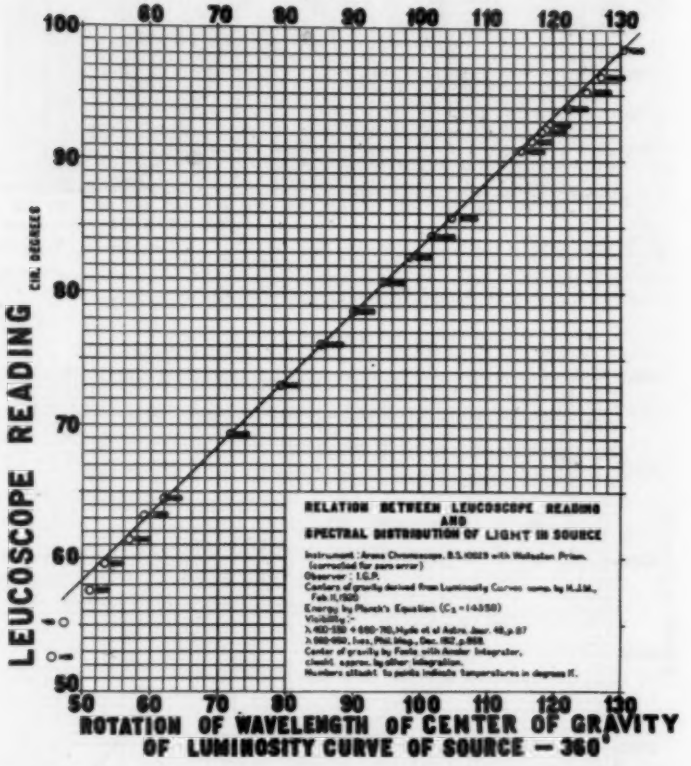
FIG. 10.



Relation of the Wave Length of Centre of Gravity of Spectral Distribution of Light to Temperature of the Source. Energy distribution by Planck's formula (c_2=14350).
Visibility:—Solid curve: Average data, 400–550 and 660–710 millimicrons, Hyde, Forsythe & Cady, *Astrop. J.* 48, p. 87. 560–650 millimicrons, Ives, *Phil. Mag.*, Dec., 1912, p. 859.
Solid circles: Foote { Data by Coblentz
Crosses : McNicholas { and Emerson,
Open circles: Priest { *B. S. Sci. Pap.*, 303, pp. 184–185.

unaffected by great uncertainties of observation and computation. It is impossible to say at present whether the deviations for temperatures less than 1250° K and greater than 4000° K are real or due to these uncertainties. This relation has been retested for the limited temperature range 1700° to 3000°K by using the data

FIG. 11.

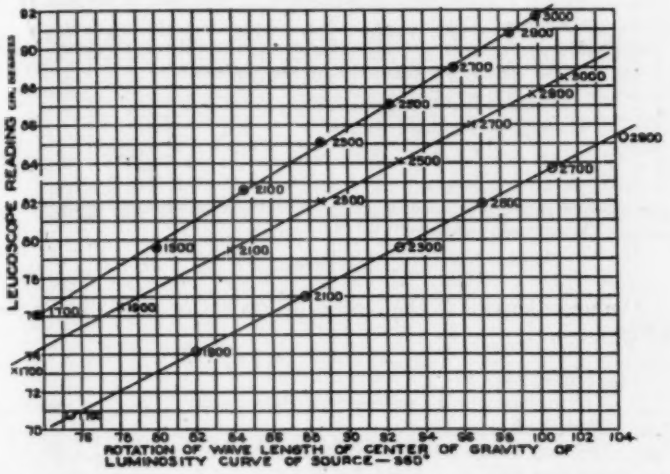

LEUCOSCOPE READING
CIR. DEGREES
ROTATION OF WAVELENGTH OF CENTER OF GRAVITY OF LUMINOSITY CURVE OF SOURCE — 360
RELATION BETWEEN LEUCOSCOPE READING AND SPECTRAL DISTRIBUTION OF LIGHT IN SOURCE

shown in Fig. 7. In this case the individual "luminosity curves" for each observer have been computed at different temperatures from *his own* visibility as given by Coblentz and Emerson.[52] The remaining steps of the reduction being carried through as outlined

[52] *B. S. Sci. Pap., No. 303*, pp. 184–185.

just above, we obtain the graphs shown in Fig. 12, which is plotted in the same way as Fig. 11. It will be noticed that the relation is linear for each observer, but that both the slope and the intercepts depend upon the individual.

FIG. 12.



Relation Between Leucoscope Reading and Spectral Distribution of Light from the Source for Three Observers.
Solid circles: Foote.
Crosses: McNicholas.
Open circles: Priest.
Numbers attached to the points indicate temperatures in degrees K.

2. *The Essential Condition That is Satisfied in Making the Leucoscope Setting.*

The second law derived from the observations recorded in this paper may be stated as follows:

The condition which is satisfied when the leucoscopic match is made according to Koenig's criterion is that the wave lengths of the spectral centres of gravity of the light of the source[33] and the two images in the leucoscope are coincident or nearly so.[34]

---

[33] Centre of gravity or so-called "centre of area" of "luminosity curve."

[34] Cf. Priest: "Relation Between Quality of Color and Spectral Distribution," *Jour. Op. Soc. Am.*, Sept., 1920.

This condition is illustrated for two particular temperatures, namely 2000° K and 3000° K in Figs. 13 and 14. The graphs in these figures represent, respectively:

1. *Solid curve*, spectral distributon of light (energy times visibility) for the given temperature, computed on the basis of Planck's equation (for $c_2 = 14350$) and visibility data as indicated in the legends of the figures.
2. *Dashed curve*, spectral distribution of light in the extraordinary image in the leucoscope, computed by the formula:

   $$(\text{Planck's Function})_\lambda \, (\text{Visibility})_\lambda \, \sin^2 (\phi - 20\,\alpha_\lambda)$$

   where ϕ = leucoscope reading.

   α_λ = rotation of plane of polarization by one millimeter of quartz, for wave length, λ.
3. *Dotted curve*, spectral distribution of light in the ordinary image in the leucoscope, computed[55] by the formula:

   $$(\text{Planck's Function})_\lambda \, (\text{Visibility})_\lambda \, \cos^2 (\phi - 20\alpha_\lambda).$$

The wave-lengths of the centres of gravity of these curves are as follows:

Temperature 2000° K.	
Extraordinary Image (relatively, slightly bluish)	581.5mμ
Black Body	582.6
Ordinary Image (relatively, slightly yellowish)	583.2
Temperature 3000° K.	
Extraordinary Image (relatively, slightly bluish)	568.9
Black Body	570.8
Ordinary Image (relatively, slightly yellowish)	571.9

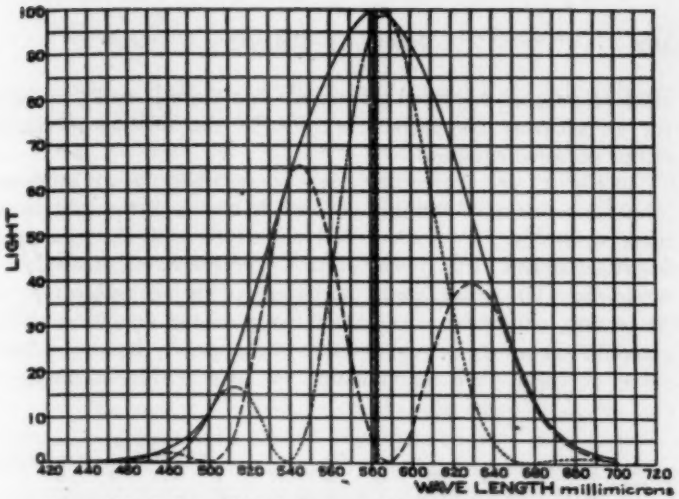
VI. EXPERIMENTS ON LEUCOSCOPIC DETERMINATION OF THE QUALITY OF SUNLIGHT AND ITS DIURNAL VARIATION.

My average leucoscope reading for sunlight on a magnesium carbonate block, between 11 o'clock and 1 o'clock, February 20, 1920, at Washington, was about 94°+. Koenig gives 90.5° for his observation on sunlight,[56] but records neither the date nor the hour of observation. This is approximately equal to my readings at 8 A.M. and 4:30 P.M. The higher latitude of Koenig's station (Berlin, Germany) would make his reading lower than

[55] For computation of $\sin^2 (\phi - 20\alpha_\lambda)$ and $\cos^2 (\phi - 20\alpha_\lambda)$ see Appendix I.

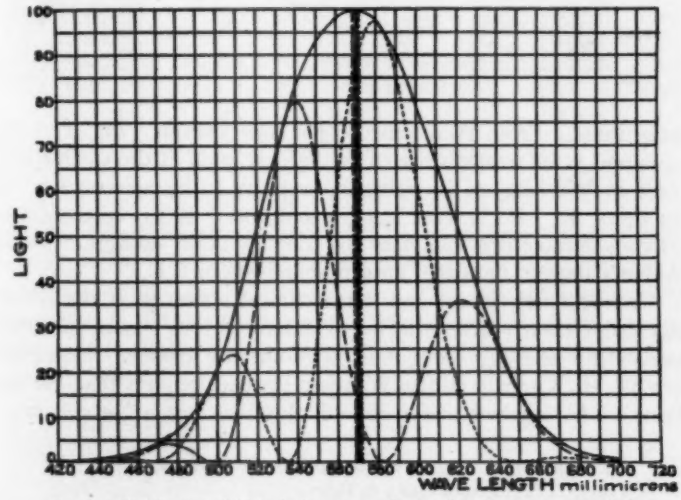
[56] *Ann. der Phy. und Chem.*, 17, p. 1004.

FIG. 13.



Spectral Distributions of Light in Leucoscope Images for Temperature 2000° K.
Energy by Planck's formula (c_2=14350).
Visibility: λ, 560–650, H. E. Ives, *Phil. Mag.*, Dec., 1912, p. 859. λ, 410–550 and 660 – 710, Hyde, Forsythe and Cady, *Astro. Jour.*, 48, p. 87.
Solid curve: source, (Planck's function) × (visibility).
Dashed curve: extraordinary image, (Planck's function) × (visibility) $\sin^2(76.1° - 20a_\lambda)$.
Dotted curve: ordinary image, (Planck's function) × (visibility) $\cos^2(76.1° - 20a_\lambda)$.
Vertical lines at about λ=582 indicate centres of gravity, solid, dashed and dotted having same significance as above.

FIG. 14.

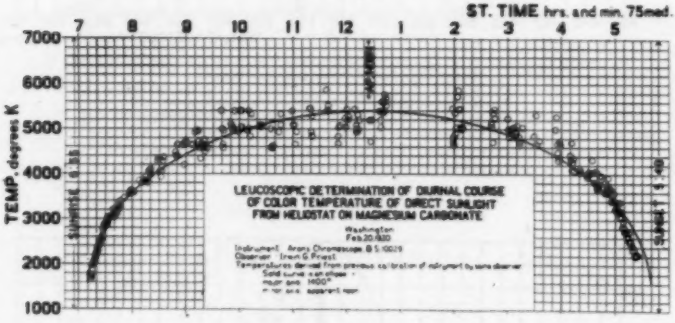


Spectral Distribution of Light in Leucoscope Images for Temperature 3000° K.
Energy by Planck's formula (c_2=14350).
Visibility: λ, 560–650, H. E. Ives, *Phil. Mag.*, Dec., 1912, p. 859. λ, 410–550 and 660–710, Hyde, Forsythe and Cady, *Astrop. Jour.* 48. p. 87.
Solid curve: source, (Planck's function) × (visibility).
Dashed curve: extraordinary image, (Planck's function) × (visibility) $\sin^2(85.7° - 20a_\lambda)$.
Dotted curve: ordinary image, (Planck's function) × (visibility) $\cos^2(85.7° - 20a_\lambda)$.
Vertical lines at about λ=570 indicate centres of gravity, solid, dashed and dotted having same significance as above.

mine because of increased air mass,[57] but there is really no basis for an *accurate* comparison because of the unknown relation of our personal equations.

In Fig. 15 are shown one day's observations on the apparent color temperature of sunlight derived by means of the calibration curve shown in Fig. 6 from determinations with the apparatus described above. *Each point plotted represents only a single observation.* The observations above 4000° K are subject to an uncertainty of 100° to 200°; but many of the deviations from a smooth curve may be real and due to changes in the atmosphere. Some of them were accompanied by large sudden changes in

FIG. 15.



brightness. From these leucoscopic observations (Fig. 15) the apparent color temperature of sunlight at noon at the earth's surface in Washington in February appears to be about 5200° K to 5400° K. H. E. Ives has selected 5000° K as representative of considerable previous data for average noon sunlight,[58] while Abbot's data[59] indicates approximately 6000° K.

To ordinary casual and non-technical observation the whole day from shortly after sunrise to shortly before sunset appeared very clear, the sky being blue without any clouds. However, Dr. H. H. Kimball, of the Weather Bureau, reports that, on the basis of his pyrheliometer record, this was not a "good day."

[57] Cf. discussion of Fig. 15, in third paragraph following this.
[58] *Trans. I. E. S.*, April, 1910, p. 193.
[59] Priest: *Phy. Rev.* (2), 11, p. 502, Fig. 1.

"There was a great deal of haze in the atmosphere which made the pyrheliometer readings quite irregular."[60]

Doctor Kimball has replotted the logarithms of these temperatures against air mass, and, extrapolating this curve to zero air mass, he finds 6500° K for the color temperature of the sun. The temperature of the sun hitherto derived by various methods appears to lie between 5800° K and 7000° K.[61] I would not attach any importance to the value found from my single day's observation; and give it merely to illustrate the use of the instrument.

Leucoscopic observations which I have made on daylight lead to the following conclusions:

(1) The quality of color of the densely overcast sky is very uniform in different directions; is subject to little diurnal variation (within 4 or 5 hours of noon); and is about the same as *sunlight outside the earth's atmosphere.* This conclusion is based upon the following values of color temperature derived from observations made by pointing the leucoscope (Arons chromoscope as described above) directly at the sky in Washington:

Date	Hour	Approximate part of sky	Condition of sky	Temp. degrees, K
Feb. 5, 1920	12:50 P.M.	60° South from Zenith	Uniform overcast. Mist.	6300
Feb. 5, 1920	1:00 P.M.	60° North from Zenith	Ditto	6500
Feb. 5, 1920	5:00 P.M.	60° South from Zenith	Ditto	6500
Feb. 6, 1920	9:00 A.M.	60° South from Zenith	Uniform overcast. Dense snow-storm.	6500

(2) The difference in color of a horizontal non-selective surface illuminated by sun and sky together and by the sky alone is strikingly shown by the leucoscope. The following are color temperatures found under these circumstances at about 4 P.M., February 11, 1920, the sky being blue with thin white clouds.

Sun and sky together	5700° K
Sky alone	7400

[60] Letter, Kimball to Priest, Oct. 1, 1920.

[61] Smithsonian Physical Tables, 7th Ed. (year 1920). Table 549, p. 418.

In considering the applicability of the leucoscope to field investigations of the color of sunlight and daylight, it is perhaps worth while to emphasize again the following features:

(1) Its portability.

(2) The extreme rapidity with which observations can be made.

(3) The absence of any comparison source or accessory apparatus demanding the observer's attention.

VII. GENERAL SUMMARY AND CONCLUSION.

This paper has given an account of a new study of the leucoscope from the point of view of its pyrometric calibration. The complete calibration curve from about 1000° to 7000° K has been determined, at least approximately, for one observer; and more careful and accurate calibrations from 1700° to 2400° K have been determined for three observers. The questions of precision, personal equation, the reproducibility of observations at fixed temperatures and the practical application of the instrument to pyrometry and the color grading of light sources have been discussed rather fully. The possible utility of the instrument in industrial pyrometry, the color grading of light sources, and the study of the color of daylight has been pointed out and illustrations of its use given. Two new laws of the instrument have been formulated.

The applicability of the leucoscope to the study of color vision has been scarcely touched upon in this paper because the author believes it would be futile to discuss this phase of the subject without much more extensive statistical data on a large number of observers of known characteristics in regard to visibility, hue discrimination and color-blindness. It seems, however, that the data given in this paper should be of fundamental importance in elucidating the physiological theory of the leucoscope. It is not unlikely that the instrument would prove useful in the study of color vision, as was indeed long ago affirmed by Brodhun.[62] However, observations of several color-blind observers recently conducted here by Mr. C. M. Blackburn, show that these observers are quite unable to make *any* consistent observations, which appears to be entirely out of accord with Brodhun's findings.[63] This

[62] *Ann. der Phy. und Chem.*, **34**, p. 918.

[63] Brodhun: *Loc. cit.*, Appendix II, this paper.

discrepancy may perhaps be due to our omission of making a brilliance match simultaneously with the color quality match. This question requires further investigation.

It is planned to publish data upon a number of other observers in a subsequent paper.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C.
November 2, 1920.

P. S. (Added to proof Dec. 3, 1920).—Since writing the above the author has devised a much more accurate method of setting up the color temperature scale from 3000° to 7000° K than that given in this paper (Sec. II, 2, and Figs. 3 and 4). This method will be described in a later number of this Journal under title: "A Method of Obtaining Radiant Energy Having the Spectral Distribution of a Complete Radiator at Very High Temperatures." Data on the actual spectral distribution of B. S. Lamp 1717 used in this paper as standard of color temperature at 2830° K will also be given in the forthcoming paper.—I. G. P.

APPENDIX I.

The Computation of Spectral Transmission by Rotatory Dispersion.

If a crystalline quartz plate, with plane surfaces perpendicular to the optic axis, be placed between nicol prisms so that the optic axis is coincident with the line of sight through the nicols, the system so constituted is, in effect, a selective light filter of adjustable spectral transmission. The transmission is a function of:

(1) the wave length, λ;
(2) the thickness of the quartz plate, b;
(3) the angle through which one of the nicols is rotated relative to the other, in the same direction as the rotation of the plane of polarization by the quartz and measured from zero for the position of extinction with the quartz removed, ϕ.

The relative transmission is given by the formula:

$$\sin^2(\phi - b\alpha_\lambda)$$

where α_λ = rotation by unit thickness of quartz for wave-length λ.

The computation chart, Fig. 16, has been prepared to facilitate the evaluation of this function for any value of ϕ and selected values of λ, for b = 1.000 mm. Values of ϕ are plotted as abscissa and values of $\sin^2(\phi - \alpha_\lambda)$ as ordinate.[64] The scale at the bottom is to be used in connection with the scale on the left; and the scale at the top, with that on the right. Each curve in these figures relates to a particular value of λ, indicated in the margins by numbers attached to the curves by arrows. By use of this chart, the spectral curve showing the relative transmission of quartz-nicol systems such as used in this investigation to obtain spectral energy distributions corresponding to high temperatures may be quickly plotted. Such plots for selected values of ϕ are shown in Fig. 17.

If a calcite rhomb or double image prism (Wollaston) be substituted for one of the nicols, as in the leucoscope, the relative transmissions corresponding to the two images will be:

$$\text{extraordinary image, } \sin^2(\phi - b\alpha_\lambda)$$

$$\text{ordinary image, } \cos^2(\phi - b\alpha_\lambda)$$

Figs. 18 to 21 (similar to Fig. 16) provide for evaluating these functions for the standard leucoscope quartz thickness of 20.000 mm. In order to avoid confusion of the curves, it has been necessary to prepare four separate figures each covering a limited range of wave-lengths.

The method of using these charts (Figs. 16, 18, 19, 20, 21) should be sufficiently obvious without further explanation.

Curves of relative spectral transmission derived from these computation curves for b = 20.000 mm. and selected values of ϕ (50, 60, 70, 80, 90°) covering nearly our complete range of leucoscope readings are shown in Fig. 22. They will be of interest to those who care to analyze critically the action of the leucoscope.

For further treatment of the above subject, reference may be made to the following:

1. Koenig: *Ann. der Phy. und Chem.*, 17, pp. 994–995.
2. Brodhun: *Ann. der Phy. und Chem.*, 34, pp. 897–918, particularly Fig. 3.
3. Arons: *Ein Chromoskop, Ann. der Phy.* (4), 33, pp. 799–832; 1910.
4. Priest: *Phy. Rev.* (2), 10, p. 208, Aug., 1917; *Phy. Rev.* (2), 11, p. 502, June, 1918. The Application of Rotatory Dispersion to Colorimetry (forthcoming paper.)

[64] Computed from Lowry's rotatory dispersion data, *Phil. Trans., Roy. Soc., Lon. A.*, 212, pp. 288–289.

FIG. 16.

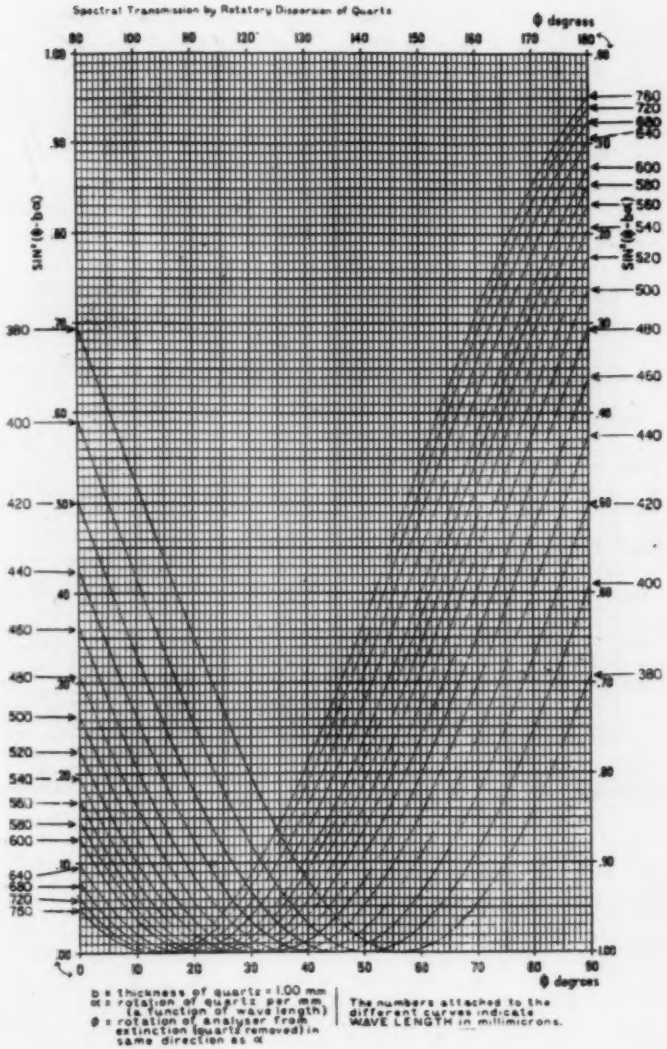
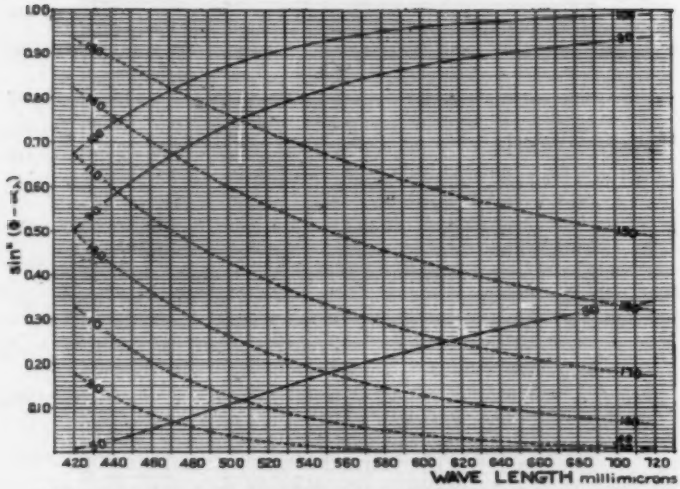

Spectral Transmission by Rotatory Dispersion of Quartz
φ degrees
SIN²(φ - bα)
SIN²(φ + bα)
780
720
680
640
600
580
560
540
520
500
480
460
440
420
400
380
φ degrees
b = thickness of quartz = 1.00 mm
α = rotation of quartz per mm. (a function of wave length)
φ = rotation of analyser from extinction (quartz removed) in same direction as α
The numbers attached to the different curves indicate WAVE LENGTH in millimicrons.

FIG. 17



Relative Spectral Transmission of a One-millimeter Quartz plate between Nicol Prisms. Numbers attached to the curves indicate values of the angle ϕ in degrees. (Cf. Text, Appendix I.)

FIG. 18.

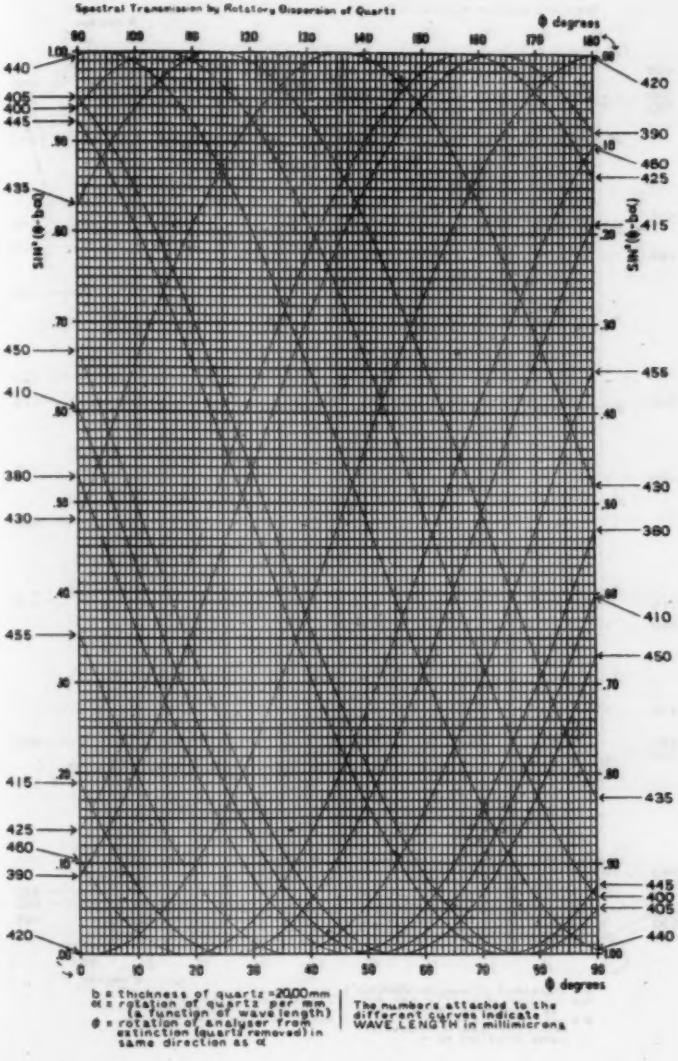

Spectral Transmission by Rotatory Dispersion of Quartz
φ degrees
sin² (φ-bα)
440
405
400
445
435
450
410
380
430
455
415
425
460
390
420
420
390
460
425
415
455
430
380
410
450
435
445
400
405
440
0 10 20 30 40 50 60 70 80 90
φ degrees
b = thickness of quartz = 20.00mm
α = rotation of quartz per mm (a function of wavelength)
φ = rotation of analyser from extinction (quartz removed) in same direction as α
The numbers attached to the different curves indicate WAVE LENGTH in millimicrons

FIG. 19.

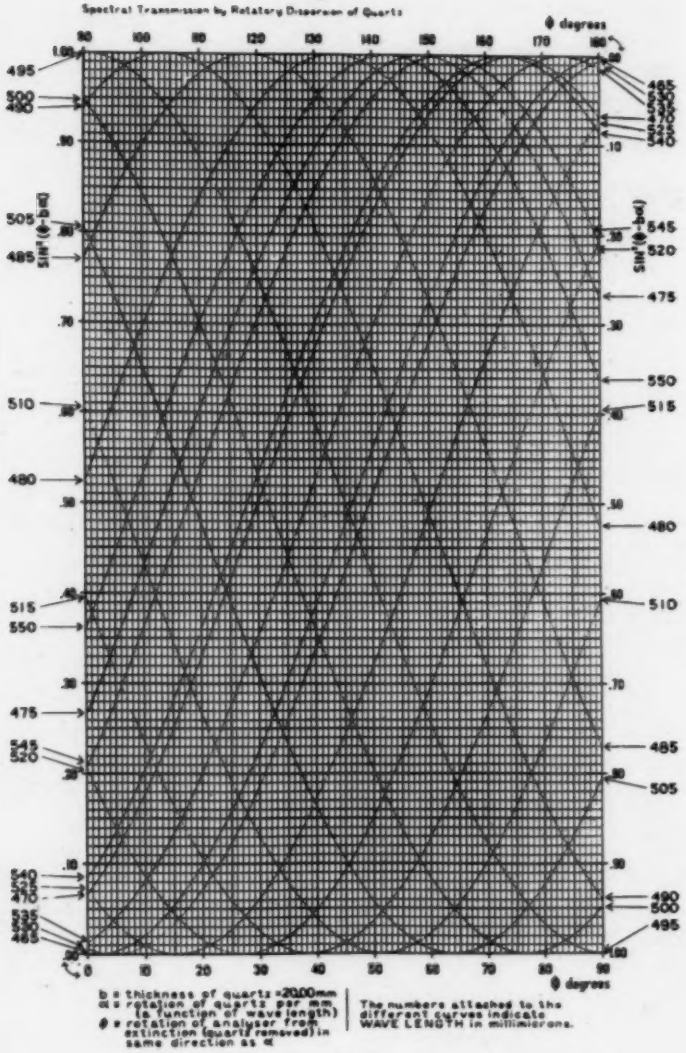

Spectral Transmission by Rotatory Dispersion of Quartz
φ degrees
90 100 110 120 130 140 150 160 170 180
1.00
495
500
490
.90
505
485
.80
.70
510
480
.60
515
550
.50
475
545
520
.40
540
535
530
525
485
.30
.20
.10
0
10 20 30 40 50 60 70 80 90
φ degrees
sin² (φ-bα)
485
520
475
550
515
480
510
485
505
490
500
495
b = thickness of quartz = 20.00 mm
α = rotation of quartz per mm. (a function of wave length)
φ = rotation of analyser from extinction (quartz removed) in same direction as α
The numbers attached to the different curves indicate WAVE LENGTH in millimicrons.

FIG. 20.

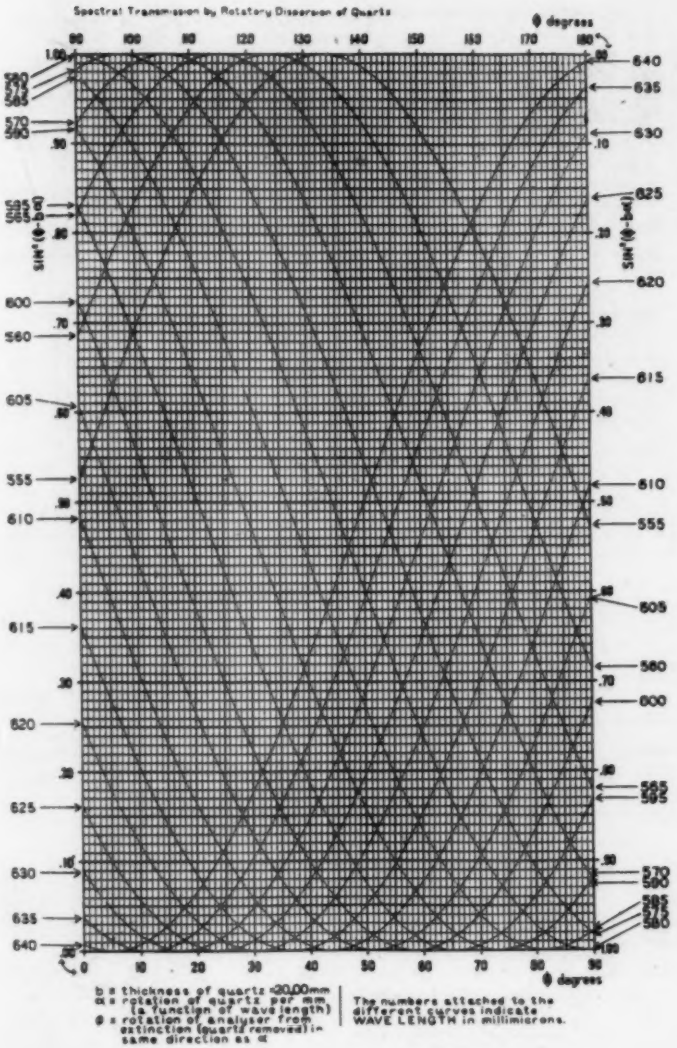

Spectral Transmission by Rotatory Dispersion of Quartz
φ degrees
90 100 110 120 130 140 150 160 170 180
640
635
630
625
620
615
610
605
600
595
590
585
580
575
570
565
560
555
SIN²(φ-bα)
0 10 20 30 40 50 60 70 80 90
φ degrees
b = thickness of quartz =20.00mm
α = rotation of quartz per mm. (a function of wave length)
φ = rotation of analyser from extinction (quartz removed) in same direction as α
The numbers attached to the different curves indicate WAVE LENGTH in millimicrons.

FIG. 21.

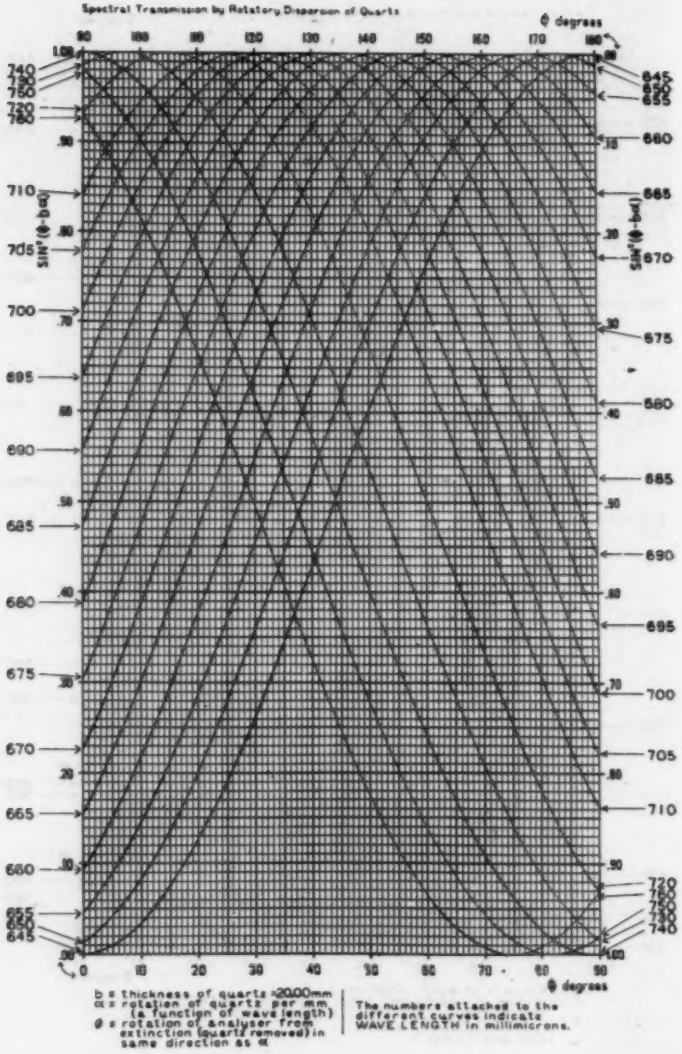
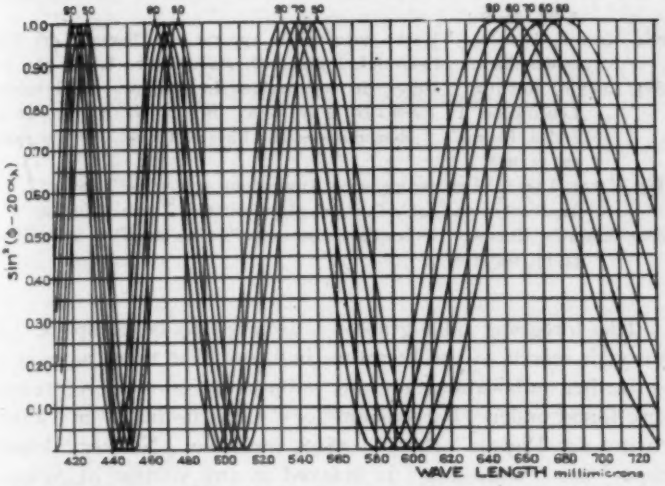

Spectral Transmission by Rotatory Dispersion of Quartz
φ degrees
90 100 110 120 130 140 150 160 170 180
LSB
740
730
750
720
760
710
705
700
695
690
685
680
675
670
665
660
655
650
645
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
SIN²(φ - bα)
645
650
655
660
665
670
675
680
685
690
695
700
705
710
720
760
750
730
740
.00
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
0 10 20 30 40 50 60 70 80 90
φ degrees
b = thickness of quartz =2000mm
α = rotation of quartz per mm (a function of wave length)
φ = rotation of analyser from extinction (quartz removed) in same direction as α
The numbers attached to the different curves indicate WAVE LENGTH in millimicrons.

FIG. 22.



Relative Spectral Transmission of a Twenty-millimeter Quartz Plate between Nicol Prisms. Numbers attached to the curves indicate values of the angle ϕ in degrees. (Cf. Text, Appendix I.) These curves show the transmission for the extraordinary image in the leucoscope, ϕ being understood as the leucoscope reading. The transmission for the ordinary image may be obtained by reversing the ordinate scale.

APPENDIX II.

Bibliography.

(CHRONOLOGIC)

1863. ROSE, EDM.: *Archiv für path. Anat. und Physiol.* (Virchow's Archiv) (*2*), **8**, pp. 81–82, and 35–46.

Description of a "Farbenmesser" which must be regarded as the prototype of the leucoscope is given as an appendix to a paper entitled "Ueber die Hallucinationen im Santonrausch." (Cf. Norris and Oliver: "System of Diseases of the Eye," Vol. 2, p. 347.)

1878. KITAO, DIRO: "Zur Farbenlehre," *Inaug. Diss., Goettingen.* Also *Ann. der Phy.*, Beib, **4**, pp. 51–53; 1880.

1882. KOENIG, ARTHUR (and HELMHOLTZ, in discussion): "Ueber das Leucoscope." *Verh. der Phy. Gesel*, Berlin, Nr. 2, pp. 23–28, Feb. 3, 1882.

1882. KOENIG, ARTHUR: "Das Leucoscope und einige mit demselben gemachte Beobachtungen." *Ann. der Phy. und Chem.*, **17**, pp. 990–1008.

1882. KOENIG, ARTHUR: "Neue Beobachtungen mit dem Leucoscope." *Verh. der Phy. Gesel*, Berlin, Nr. 12, pp. 90–94.

1883. KOENIG, ARTHUR: "Das Leucoscope und seine Theorie." *Zeit. für Instk.*, 3, pp. 20–26.

1884. KOENIG, ARTHUR: "Ueber einen neuen Apparat zur Diagnose der Farbenblindheit." *Centralblatt für prak. Augenheilk.*, 8, pp. 375–377.

1884. KOENIG, ARTHUR: "Ueber ein verinfachtes Leucoscope. (Ophthalmo-Leucoscope.") *Verh. der Phy. Gesel*, Berlin, Nr. 11, pp. 41–43. (Also, Koenig's "Abhandlungen zur Physiol. Optik," Leipzig, 1903, pp. 34–36.)

1885. KITAO, DIRO: "Leucoscope seine Anwendung und seine Theorie." *Abhandlungen des Tokio Daigaku* (Univerität zu Tokio), No. 12.

1888. BRODHUN, EUGEN: "Ueber das Leucoscope." *Ann. der Phy. und Chem.*, 34, pp. 897–918.

The foregoing bibliography is believed to be complete. A thorough search of the literature indicates that there have been no further publications on this subject. No other references were found under "Farbensinn" or "Optische Inst.," in "Fortschritte der Physik," 1885 to 1898, inclusive. Neither "leucoscope" nor "leucoskop" is indexed in any volume of *Science Abstracts*, 1898 to date, under any of the headings where it might logically appear: viz., "Vision," "Photometry," "Apparatus and Instruments," "Measurements and Use of Instruments."

Professor Nagaoka, who was acquainted with Kitao, has informed the author that neither Kitao, who died about ten years ago, nor anyone else in Japan has published anything further on the leucoscope.

The leucoscope is not indexed and apparently not mentioned in any of the following books:

"Enc. Brit.," 1910–11.
"Intern. Enc.," 1918.
WINKELMANN: "Handbuch der Physik," 1906.
WUELLNER: "Experimentalphysik," 5th Ed., 1899.
KORSCHELT (and others): "Handwörterbuch der Naturwissenschaften," 1912.
ABNEY: "Colour Measurement and Mixture," 1891.
ABNEY: "Researches in Colour Vision," 1913.
EDRIDGE-GREEN: "Colour Blindness," 1909.
KOELLNER: "Stoerungen des Farbensinnes," 1912.
ROSMANIT: "Feststellungen der Farbentüchtigkeit," 1914.
LUCKIESH: "Color and its Applications," 1915.
PARSONS: "Introduction to the Study of Colour Vision," 1915.

Although its importance in this field is evident, it is not mentioned in any of the following papers on color grading of light sources:

IVES, H. E.: "Color Measurements of Illuminants—a Résumé." *Trans. I. E. S.*, April, 1910, p. 189.

BLOCK: "Kennzeichnung der Farbe des Lichtes." *Electrot. Zs. Heft*, **46**, p. 1306; 1913.

JONES: "The Color of Illuminants." *Trans. I. E. S.*, **9**, p. 687; 1914.

HYDE AND FORSYTHE: "The Quality of Light from an Illuminant as Indicated by its Color Temperature." *Jour. Frank. Inst.*, **183**, pp. 353–354; 1917.

That it is practically unknown in pyrometry is indicated by the fact that it is not indexed and apparently not mentioned in either:

(1) BURGESS AND LECHATELIER, "High Temperature Measurements," 1912,

or

(2) "Symposium on Pyrometry," published by *Am. Inst. of Min. and Metal. Eng.*, 1920.

NOTE ON A NEW METHOD OF JOINING GLASS.*

BY

C. O. FAIRCHILD.

Introduction.—The need for flat glass windows for incandescent lamp bulbs led the writer to seek a new method for accomplishing the fusion of glass joints without appreciable deformation of the surfaces. Such lamps were desirable for studying the effects of diffraction caused by the lamp filament in an optical pyrometer of the so-called disappearing filament, or Morse, type, because the diffraction effect was obscured by the imperfect surfaces of lamp bulbs of blown glass. Lamps have been constructed by the new method, as shown in Fig. 3, C having two flat windows, the transmission of which can be easily measured and which give an undistorted telescopic image of the filament.

Parker and Dalladay [1] have developed a precision method of uniting optical glass which depends upon optical contact and pressure, the glass being raised to a temperature well below its annealing range. Their method is particularly suitable for the construction of flat-sided cells in case most precise flatness is required. Its disadvantages lie in the necessity of obtaining perfect fit of the parts to be joined, by careful polishing and cleansing, and the time required (about one hour) for junction to be completed. Its application is restricted to glasses having annealing points which differ by not more than about 50°. The method devised by the writer fails only for glasses which have too widely different coefficients of thermal expansion.

Method.—Briefly the process consists in maintaining the glass at a temperature sufficiently high to avoid cracking while applying heat locally, the temperature of the main body of the glass being one at which undue distortion will not occur. The body temperature necessary is always near the annealing temperature and this depends, of course, primarily upon the kind of glass, but is also dependent to some extent upon the dimensions of the

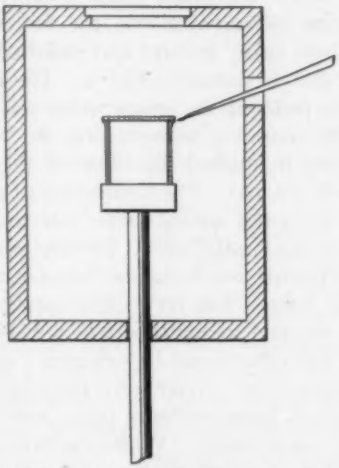
* Published by permission of the Director, Bureau of Standards.

[1] Parker and Dalladay: *Faraday Soc. Trans.*, 12, pp. 305–312. For short bibliography on thermal and other properties of glass see Tool and Valasek, *B. S. Sci. Papers*, No. 358, 1920.

article. By this method complete fusion of the junction can be accomplished without propagating beyond a restricted portion near the joint the stresses occasioned by local heating; hence it is applicable where a slight deformation at the junction does not impair the usefulness of the article.

For the purpose of maintaining the body of the glass at the proper temperature during local fusion of a joint an electric furnace was constructed, as shown in Fig. 1, having a mica

FIG. 1.



Cross section of furnace and glass tube and disc supported within on a pedestal.

window [2] above and a small hole in the side for introduction of a blowpipe. It is provided with a centrally located pedestal, which extends through a closely fitting hole in the bottom, upon which glass objects can be placed and rotated about a vertical axis. A sodium flame backed by an incandescent lamp is used for illuminating the interior—the sodium flame furnishing monochromatic illumination for interference fringes between polished surfaces nearly in contact and the white light furnishing the general illumination of the object. For measuring the furnace temperature a small platinum-rhodium thermocouple is inserted through

[2] Pyrex glass or fused quartz would be better because mica soon splits and becomes more opaque with continued heating.

the furnace cover and arranged so as to place its hot junction in contact either with the furnace wall or with the glass being treated. A blowpipe having a millimeter orifice is used with an oxy-gas flame about 1 cm long.

The furnace can be quickly heated to a required temperature and held there, so that a small glass article can be raised to temperatures above the annealing temperature, the junction completed by application of the flame, and cooling initiated, before the glass has sufficient time to appreciably change its shape.

Because the writer's primary interest lay in construction of incandescent lamps, as stated above, the first experiments were performed on short tubes ground and polished on one end and topped by a flat disc as shown in Fig. 1. The tube with the disc was placed on the pedestal, the temperature was rapidly raised to slightly above the annealing temperature, the flame inserted into the furnace so that it touched the edges of the disc and tube as the pedestal slowly rotated. The completion of the joint was thus accomplished in but a few seconds after inserting the blowpipe.

The first trial was satisfactory for the primary purpose in mind, the disc showing no distortion beyond two mm from the inner edge of the joint. The very slight application of the flame required in case the end of the tube was polished, indicated that fine grinding of the tube would be sufficient; also that flaring of the ends was unnecessary. After some practice quite satisfactory joints were obtained, using unflared tubes with the ends finished by grinding with wash emery. While the first experiments were tried having the disc of exactly the same glass as the tube, ordinary American plate was found quite satisfactory to use with common lead glass tubing. The annealing temperature of the plate glass used was approximately 565° C. and that of the tubing 460° C.[3] The coefficients of thermal expansion in the low range were respectively, 0.101×10^{-4} and 0.09×10^{-4}. There is quite an advantage in using glass for the disc which has a higher annealing temperature than that of the tube. Since the glass was thin, sudden application of heat to the disc at a temperature as low as 470° did not crack it and the unavoidable strains were not serious. They were probably greater than the allowable strains in a polarimeter tube, but were so slight that the incandescent lamps made could easily be heated over a bare flame during their exhaustion.

[3] Peters and Cragoe: *Jour. Opt. Soc. of Amer.*, **4**, 3, pp. 105–145, 1920.

Discussion of the Principles Involved.—The combined effect of low thermal conductivity of glass and the rapid change in its mobility with temperature was the single important factor leading to the development of the simple process described. As a result of low thermal conductivity *large temperature gradients may be imposed with only slight flow of heat.* When glass is heated to its annealing temperature its mobility begins to increase at a rapid rate, *experiments showing the mobility to be approximately an exponential function of the temperature.* For example, some glasses become twice as soft for every rise in temperature of 8° or 10° C.[4] These two properties permit the attainment of such a temperature gradient that the variation in mobility in a very small distance is exceedingly great. If the relation of mobility to temperature persists over wide ranges of temperature, a gradient of 100° per mm. corresponds to a change of mobility per mm of over 1000 times. Thus a piece of glass at the annealing temperature may be suddenly heated superficially without distorting more than a small part of it. The glass being heated to its annealing temperature, or slightly above it, the application of the flame to an edge quickly raises the edge far above the temperature called by Tool [5] "upper limit of the annealing range." At this latter temperature the glass has become very nearly a true viscous substance, that is, minute stresses result in flow. It is due to this fact that union is so quickly started by the flame. The local distortion occurring under the flame does not extend far and, since the body of the glass is within its annealing range stresses cannot be propagated in any appreciable amount beyond the region overheated. In some cases it was possible by watching interference fringes during the process of joining, to observe very nicely the effect of sudden expansion of the part touched by the flame, the quick union occurring, the very rapid loss of heat by radiation, and the fairly rapid return to the original configura-

FIG. 2.

Cross section of glass ring and flat cover.

[4] See ref. 1.

[5] Tool and Valasek: *B. S. Sci. Papers*, No. 358, 1920.

tion. Probably expansion forces the surfaces into contact before fusion and the force may be fairly large. Molecular forces are brought into play as soon as contact occurs. The surfaces become quite clean at the temperatures used because of the oxidation of organic matter (as dust) and the expulsion of occluded gases.

The change in the temperature coefficient of thermal expansion observed by Peters and Cragoe,[6] to take place at the annealing temperature, may play a part, and probably the best joints can be made above the annealing temperature; that is, above the temperature at which this coefficient changes from the value which persists from room temperature to the annealing temperature.

At the annealing temperature the flow of small glass articles

FIG. 3.

A. Hollow 45° prism; B. glass cell; C. optical pyrometer lamp; D. tube closed at both ends; E. glass cell with thin rim; F. compound lens fused at periphery. Line of fusion is visible as dark band.

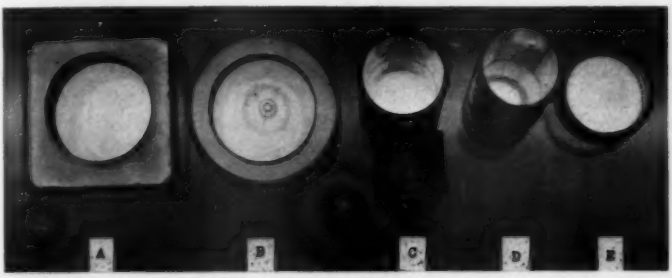
due to their own weight when unevenly supported, is exceedingly slow and the quickness with which a joint can be made by this method allows very little distortion to occur. Hence, in nearly all cases it will be best to use the annealing temperature, in which event, after completing the joint the temperature can be allowed to fall slowly without any complications for the purpose of annealing.

Applications of the Process.—A few articles of various forms have been made to determine the applicability of the process. Some of these are shown in Figs. 3 and 4. The method can also be employed for constructing absorption cells, colorimeter tubes, glass boxes, polarimeter tubes, Nessler tubes, glass-liquid prisms, lenses, etc., hæmacytometers, and even interferometer parts. In

[6] See ref. 3.

Fig. 4 the articles have been placed on a glass plane and illuminated with a mercury lamp. The hollow 45° prism shown in Fig. 3 was not flat enough to photograph as in Fig. 4. The millimeter plate glass used had not been well annealed and merely heating to the annealing temperature distorted it. A compound lens was made by fusing the periphery with the inclusion of an air film. The joint is about 2 mm wide and the air film about 0.2 mm thick at the centre. The convex part was selected with a surface of greater radius than that of the concave. The two glasses[7] used were (1) borosilicate crown, annealing temperature

FIG. 4.



Articles placed on a glass plane and illuminated with a mercury lamp. A, B, E, glass cells. C, Optical pyrometer lamp. The end down is seen to be flat to about 1 micron.; D, simple tube. The end is seen to be flat to fraction of a wave-length within 1 mm. of edge.

530°, coefficient of expansion (below 500°) 0.090×10^{-4}, and (2) medium flint, annealing temperature 450°, coefficient of expansion 0.097×10^{-4}. The lens is about 5 cms in diameter. Possibly such a lens is of little usefulness, but so far as distortion is concerned the result was satisfactory. If such a thing were of any utility, lenses could be made by carrying the weld through only a portion of the periphery, leaving an opening for the injection of Canada balsam. It may be found that glass-liquid lenses will be useful. A seeming disadvantage is the higher temperature coefficient of refraction of liquids. This would probably limit the use of such a lens to special laboratory problems. Such a lens could be easily made by welding the parts on to the two ends of a short tube, as shown in Fig. 5.

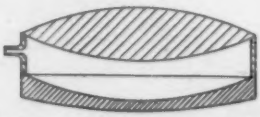
Various details of the method of making hæmacytometers

[7] See ref. 5.

have been tried but will not be described. The writer is now constructing some total reflecting glass rhombs having fused-on protecting plates for the reflecting surfaces. These are for use in a colorimeter in which the rhombs are immersed in the liquid whose transmission is being studied. A preliminary experiment has shown that the plates can be fused on very easily without distortion of more than approximately a millimetre of the surfaces at the edges of the joints.

The ordinary absorption cell with cemented sides has usually been made with a very thick rim for the purpose of cementing. This method does not require such heavy construction and for most ordinary purposes cells can be made with thin-walled tubing. Further experiments showed, however, that the thick rim was of considerable advantage in making cells with quite flat sides. It was found that a joint started by the flame at the outer edge

FIG. 5.



Cross section of suggested form of a glass-liquid lens.

in such case extended to the inner edge well beyond the parts heated above the annealing range. It became apparent that molecular attraction was brought into play, pulling the surfaces together when once molecular contact was started. In one case shown in cross section in Fig. 2, a flat disc about 5 cm in diameter and 8 mm thick, flat on one side, was bored out, affording a ring with a bearing surface 1 cm in width. The piece had not been properly annealed and cutting the hole resulted in a distortion which raised the inner edge of the ring so that a flat disc placed upon it touched only the inner edge and allowed an air film at the outer edge. Examination before the sodium flame exhibited six interference fringes. The result of joining a cover to this ring was quite unexpected. Quick fusion around the outer edge caused complete joining as far as the inner edge, pulling the periphery of the cover into contact and forcing the centre out about 10 microns. At first thought, such an effect might be assigned to fusion of the periphery and subsequent contraction.

But such action would undoubtedly have resulted in a distortion of the cover in the opposite direction. Furthermore, the amount of distortion of the cover corresponded to the original condition of the ring. In this way it is emphasized that this new method of joining glass does not require a perfect fit of the articles to be joined and that the final result is measured quantitatively by the lack of fit. Thus, in the construction of various articles the fitting may be perfected to a degree governed by the precision desired. It is particularly to be noted that examination of the piece illustrated by Fig. 2, by placing a flat test plate upon it to obtain interference fringes, gave fringes which crossed the inner edge of the joint without any displacement. There remains little doubt that had the ring been quite flat the cover would have remained undistorted. There has not been opportunity to prove this, but the action described seems fairly conclusive. We may add that only for precise work, in which case fusion by the flame is kept at a minimum, is it necessary to exercise special precautions as to particles of dust caught between surfaces. A particle of dust lodged near the outer rim is no hindrance and is entrapped, becoming invisible. A particle near the inner edge obviously prevents complete junction.

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(Continued from page 242, Vol. IV, No. 4, July, 1920.)

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CORRECTION.

On pages 392 to 394, Volume IV, in the legends under Figs. 3 to 8 inclusive, for "sunlight" read "sun's energy."

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Beginning with Volume IV, the JOURNAL of the Optical Society of America has been published regularly, bimonthly.

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